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Fluid flow in the central North Slope foreland basin, Alaska

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FLUID FLOW IN THE CENTRAL NORTH SLOPE FORELAND BASIN, ALASKA

A Thesis

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Table of Contents

Abstract

Previous studies of the areal variations in heat flow and spatial variations in formation water salinity and hydraulic head are consistent with the existence of a currently active, topographically-driven regional fluid flow regime in the National Petroleum Reserve Alaska (NPRA) portion of the western North Slope foreland basin. This conclusion is also supported by the results of numerical modeling of fluid flow and heat transport in the area. This work has now been extended to the east. The results of this study demonstrate that the Permian through Cenozoic age sediments of the central North Slope foreland basin have been significantly flushed by low salinity waters. Although isotopic analyses of these waters are not available, it is likely that they have a major meteoric component, as is the case in the NPRA immediately to the west. There may have been several periods of time in which meteoric waters were introduced into the section, including the Triassic, during the development of the Lower Cretaceous Unconformity (LCU), and following the uplift of the Brooks Range in the Upper Cretaceous. Diagenesis associated with fluid flow during the LCU may have provided pathways for later hydrocarbon migration. The introduction of meteoric water has the potential for lowering the API gravity of crude oil through water washing and/or biodegradation. However, there is no clear relation in the North Slope between salinity and API gravity. It is possible that the Prudhoe Bay oils, which are light, were emplaced following invasion of fresh waters and the overlying Kuparuk oils, which are heavier, have been significantly impacted by fresh waters following hydrocarbon migration and entrapment. By analogy in geologic setting to the NPRA, a topographically-driven fluid flow regime probably exists today in the central North Slope, but additional pressure, head, and temperature data are needed to further verify this hypothesis. There is no

clear relation between depth to the base of permafrost in the study area and the elevated temperatures at depths of 2-3 km which may reflect fluid upwelling.

Chapter 1. Introduction

Some of the most productive hydrocarbon basins in the world are situated in the foreland region of active and ancient orogenic belts (Macqueen and Leckie, 1992). Foreland basins have the potential to contain large volumes of economically significant hydrocarbons reserves (Macqueen and Leckie, 1992). Much of the North Slope foreland basin, Alaska is still relatively unexplored and has great potential for future exploration and development of natural resources (see Montgomery, 1998). In 1967, Prudhoe Bay (Fig. 1) the first and largest oil field discovery in Alaska was discovered (Montgomery, 1998). This was the beginning of the oil industry on the North Slope of Alaska, which has now grown to 19 producing oil fields (Bailey, 2005/2006). Recently, Alaska exploration has been intensified by the possible construction of a natural gas pipeline (Houseknecht and Bird, 2006). Current hydrocarbon production on the North Slope is confined to the central portion of the North Slope basin. However, hydrocarbons have been found to the west, in the National Petroleum Reserve, Alaska (NPRA) (Fig.1) (Montgomery, 1998), and there is interest in the possibility of hydrocarbon occurrences to the east in the Arctic National Wildlife Refuge (ANWR) (Fig. 1).

North Slope oils exhibit a significant range in the American Petroleum Institute (API) gravity standard. According to Werner (1987), the occurrence of low API gravity crude oil in Upper Cretaceous and Tertiary sands in the North Slope has been known since 1969. Most of the low gravity (heavy) oil (< 22.3^{o} API) occurs in the Upper Cretaceous West Sak sands and overlying Upper Cretaceous-Paleocene Ugnu sands. API gravity of the West Sak oil ranges from 16 to 22^{o} API, while API gravity of crude oil in the Ugnu sands ranges from 8 to 12^{o} API (Werner, 1987). Among the highest gravity (light) oils in the central North Slope are the 35 to the 40^{o} oils found in the Tarn and Alpine fields (Masterson, 2001). Oils in the Kuparuk and

Prudhoe Bay fields have intermediate API gravities, which range from 20 to 30 ^{o} API (Masterson, 2001).

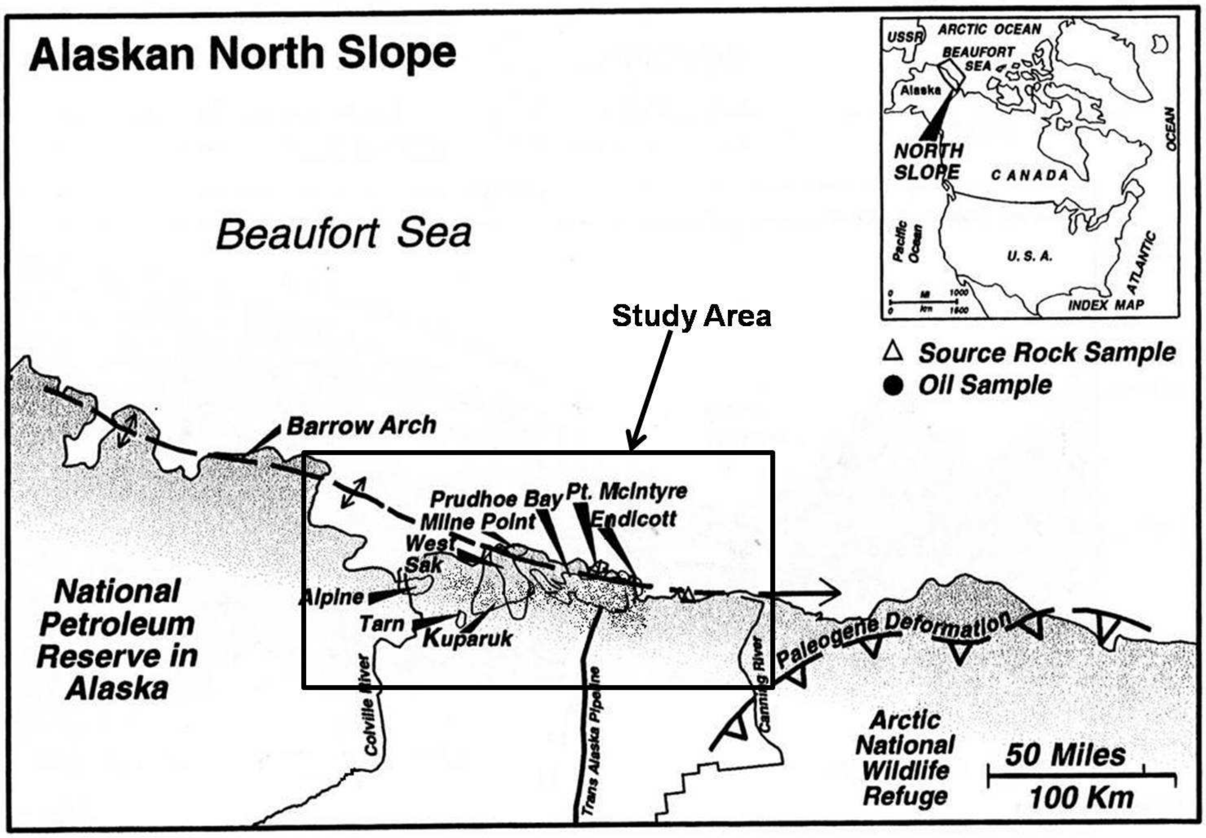


Figure 1. Current producing oil fields within the central North Slope foreland basin with the present study area outlined (basemap modified from Masterson, 2001).

According to Masterson (2001), the differences in API gravity between the Tarn-Alpine oils and the Kuparuk-Prudhoe Bay oils can be accounted for in part by a difference in source rocks: fine-grained siliciclastic sources for Tarn-Alpine and a carbonate-rich source rock for Kuparuk-Prudhoe Bay. However, Masterson (2001) also presented evidence for West Sak oils being a mixture of moderately biodegraded oils derived from the Prudhoe Bay fields and lightly biodegraded hydrocarbons derived from the underlying Kuparuk field. Both Werner (1987) and Masterson (2001) discuss evidence for biodegradation of the West Sak oils. Werner noted that the salinity of formation waters, as calculated from wireline logs ranges from 1.5 gL^{-} in the southwest Kuparuk area to over 35 gL^{-1} (sea water salinity) at Milne Point. He postulated that meteoric water and bacteria were preferentially introduced into the shallower hydrocarbon reservoirs, but stated (Werner, 1987) that "The timing of this meteoric water influx relative to oil migration is not yet known."

Dickey et al. (1987) cited many comparative studies of formation water salinities (TDS) and oil API gravities. Bockmeulen et al. (1983) and Dickey et al. (1987) looked for a possible relation between shallow heavy oil fields and the influx of meteoric waters. Heavy oil accumulations can be found throughout the world that occur at shallow depths and that are associated with relatively fresh meteoric waters (Bockmeulen et al. (1983). Although Bockemeulen et al. (1983) did not do bacterial studies on heavy oil; they did conclude that oils with low normal alkane contents in contact with low salinity bicarbonate-rich waters usually are associated with bacterial degradation.

The first extensive report on formation water salinities on the North Slope was by Woodward (1987), who calculated salinities of waters in the Triassic Ivishak sandstone from 61 spontaneous potential (SP) logs in the western part of the National Petroleum Reserve Alaska (NPRA). Woodward (1987) encountered low salinities (8-11 $g\ L^{-1}$) and identified a possible site of meteoric water recharge in the thrust-faulted Kavik Gas field in the NPRA. However, Woodward found no evidence of present day recharge outside of the Kavik area in the northern flank of the North Slope Basin. Woodward (1987) found salinities within the Ivishak sandstone (excluding the Kavik area) increased with depth, from approximately 11 to 36 $g\ L^{-1}$. Woodward concluded that recharge of the Ivishak sandstone is affected by the present day occurrence of permafrost, but questioned the long term impact of permafrost on fresh water recharge. Kharaka et al. (1985) determined from the analysis of stable hydrogen and oxygen isotopes of formation waters in the North Slope that there is an ancient meteoric component present from waters which were recharged during warmer climatic conditions than today.

The purpose of this research is to understand the potential relation between regional fluid flow in the central part of the North Slope foreland basin and the distribution and properties of the hydrocarbons. The first hypothesis tested in this research is that a topographically-driven regional groundwater flow regime exists or has existed in the past in the central North Slope basin. A second hypothesis is that the regional groundwater flow system has influenced the spatial variations in API gravity of crude oils in the central North Slope foreland basin.

This research is an extension of previous work on regional groundwater flow in the North Slope within the NPRA by Hanor et al. (2004) and Nunn et al. (2005). Hanor et al. (2004) used spatial variations in salinity calculated from SP logs, and hydraulic heads calculated from drilling mud weights and shut-in pressure tests to show that fresh water in a regional meteoric flow characterized by elevated heat flow that were documented by Deming et al. (1992) and Deming (1993). Numerical simulations of fluid flow in the NPRA by Nunn et al. (2005) found that permafrost is a primary controlling factor on the rate, pathways, and distribution of surface fluid flow recharge and discharge zones.

As in Hanor et al. (2004), evidence for present day fluid flow was determined from spatial variations in salinity, temperature, and hydraulic head. These variations are examined in the context of lithostratigraphy to identify preferential pathways of fluid flow. Salinity results calculated from SP logs were compared to available water chemistry analysis for accuracy. The API gravities of oils were compared with estimated pore water salinity to determine if there is a relation between API gravity of oils and the degree of meteoric flushing.

Chapter 2. Geologic Setting and Lithostratigraphy

Below is a summary of the geologic setting and lithostratigraphy of the central North Slope foreland basin, Alaska, based largely on work by Bird and Molenaar (1992) and Houseknecht and Bird (2006). The stratigraphic nomenclature used is consistent with a recent update by the U.S. Geological Survey (Mull et al., 2003).

The Mesozoic to Cenozoic age North Slope foreland basin, also referred to as the Colville Basin, is elongate from east to west and occupies an area of 240,000 km^2 (93,000 mi^2) on the North Slope of Alaska. The basin is bounded on the south by the Brooks Range fold and thrust belt and on the north by the Arctic Ocean (Fig. 2). The modern northern coastal boundary of the basin is a passive topographic high known as the Barrow Arch (Fig. 3), which is a failed rift shoulder that separates the Colville Basin from the northern Canadian basin.

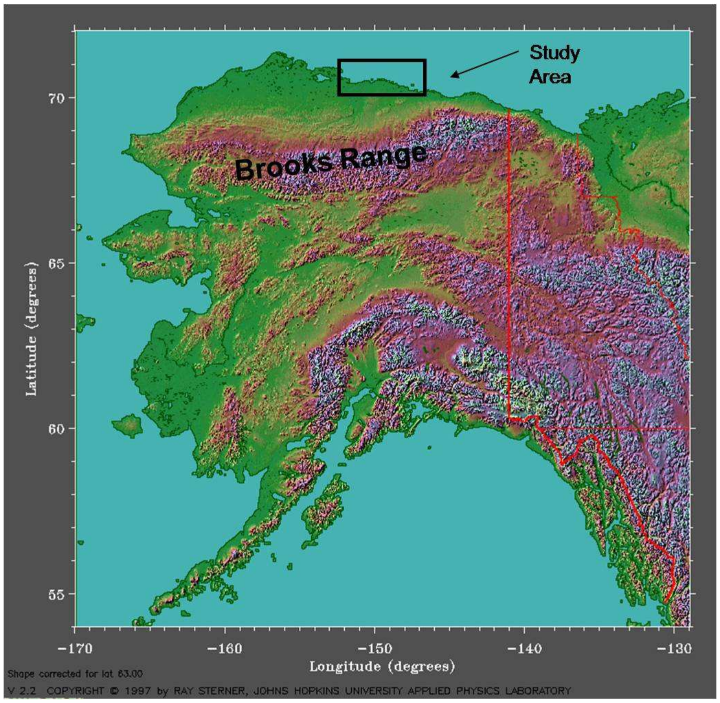


Figure 2. Topographic map of Alaska showing the Brooks Range fold and thrust belt, the Barrow Arch, and the boundary of this study area (basemap modified from Sterner, 1997 retrieved from http://gcmd.nasa.gov/records/GCMD_landform_atlas_JHUAPL.html).

Pre-foreland basin Paleozoic and Mesozoic sediments were derived from the north and were deposited on a southern-facing passive continental margin. These sediments exhibit a more basinal distal facies compared to the younger post-orogenic sediments. Post-orogenic foreland basin fill was derived from the southern Brooks Range (Fig. 3) and ranges in age from the Cretaceous to the Tertiary. The depocenter of the basin migrated northeastward with time.

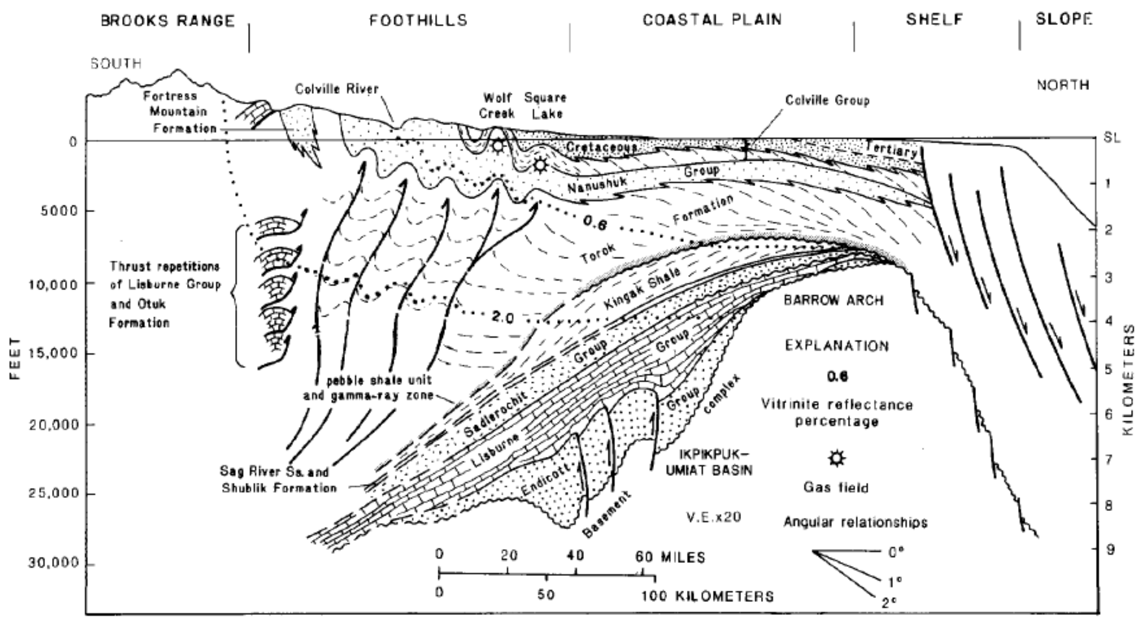


Figure 3. Structural and stratigraphic south to north cross-section of the central North Slope foreland basin showing the Brooks Range fold and thrust belt to the south (Bird and Molenaar, 1992). Cross-section is located along the western edge of the study area (Figure 1).

The North Slope foreland basin strata are divided into three distinct sedimentary rock megasequences (Figs. 4 and 5) from oldest to youngest: Ellesmerian (pre-foreland), Beaufortian (syn-rift) and the Brookian Sequence (post-foreland) (Fig. 3). These sequences are distinguished by their provenance, depositional environments, and structure.

Ellesmerian Sequence

The Mississippian through Triassic Ellesmerian sequence was sourced from the north and is characterized by carbonate and shallow marine to non-marine siliciclastic deposits. The oldest

Ellesmerian sequence deposits are classified as the Endicott Group and consist of non-marine sandstone, shale and conglomerate, which were succeeded by the shallow marine Kayak Shale. The Lisburne Group, which overlays the Kayak shale is an extensive carbonate platform sequence of limestone and dolomite. The Sadlerochit Group consists of interbedded sandstone and shale and is followed by the Ivishak sandstone, which is the main reservoir of the Prudhoe Bay oil field. The Shublik is a petroleum source rock and is composed of rich fossiliferous shale, siltstone, mudstone, and limestone.

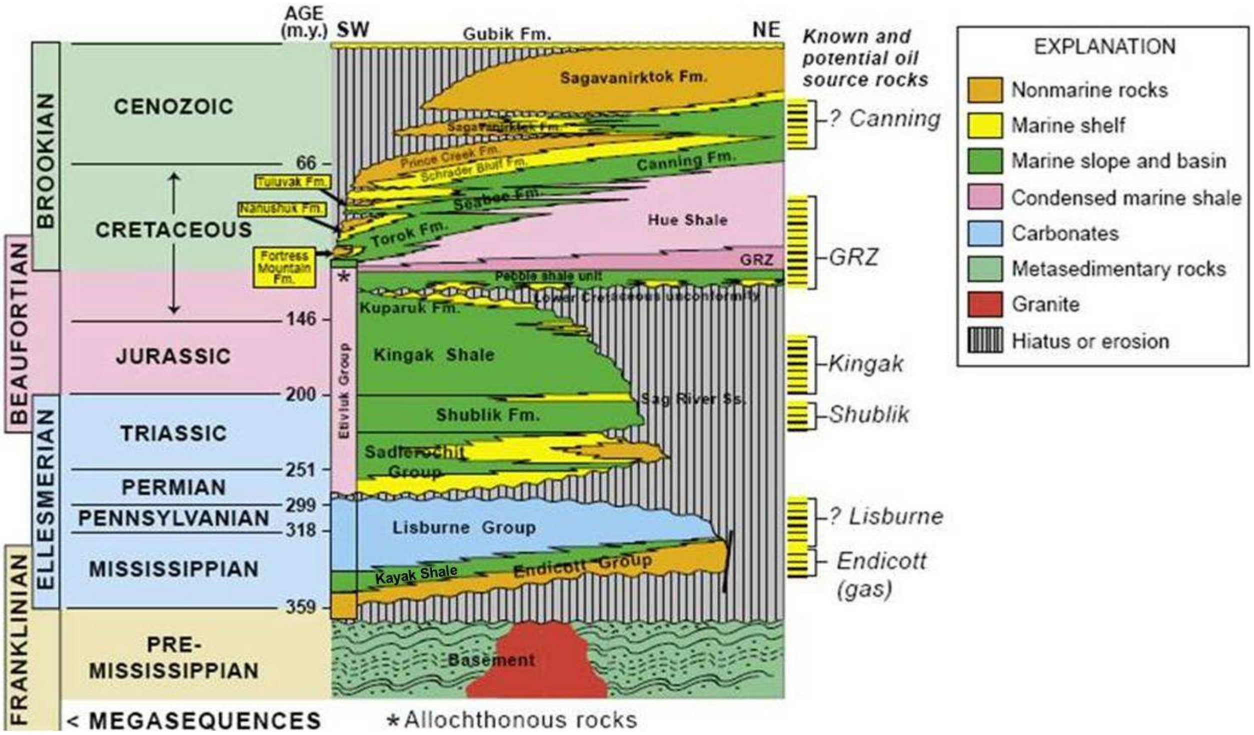


Figure 4. Generalized stratigraphic column showing the Ellesmerian, Beaufortian, and Brookian sedimentary megasequences and their depositional environments in relation to known and potential source rocks on the North Slope of Alaska. The GRZ is the highly radioactive gamma-ray zone of the Hue Shale. (modified from Houseknecht and Bird, 2006).

Beaufortian Sequence

The Jurassic through Lower Cretaceous Beaufortian sequence is also referred to as the rift sequence because its sediment source was local or from the north, and deposition occurred during a major rifting event. The Beaufortian sequence is mud-dominated with interbedded sandstones and shales. It is stratigraphically complex, varies in thickness, has multiple unconformities, and hosts both petroleum source rocks (Kingak, Shublik and Pebble Shale) and reservoir rocks (Kuparuk sands and others). Normal faults along the present northern coast have created sediment-filled half-grabens and grabens, with some fill exceeding 3 km in thickness. The failed rift margin was eventually uplifted and eroded, creating the regional Lower Cretaceous Unconformity (LCU) (Fig. 4). The LCU is also referred to as the "break-up"

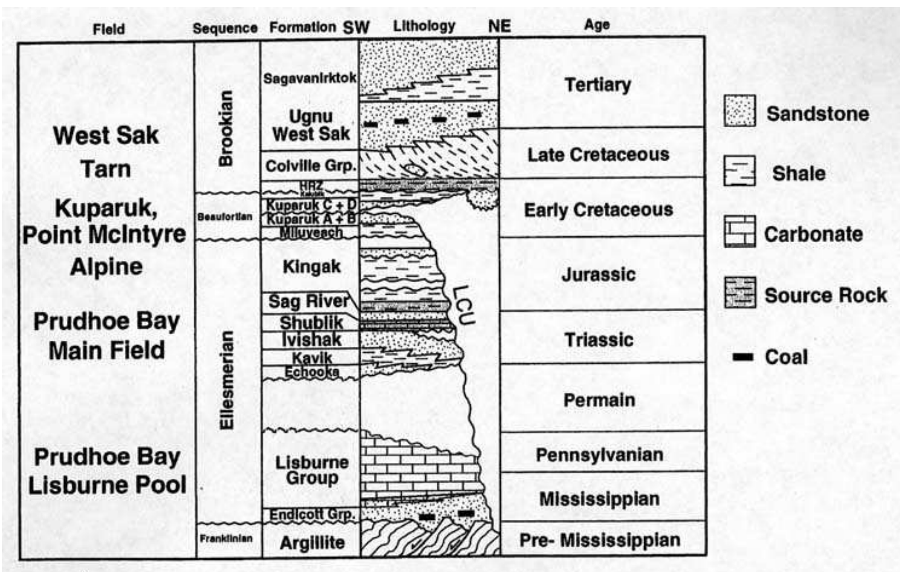


Figure 5. Generalized stratigraphic column for the Prudhoe Bay/Kuparuk River area of the Alaskan North Slope, showing lithology and the stratigraphic position of major oil fields. (From Masterson, 2001, used with permission.)

unconformity (Grantz and May, 1982) and is important in relation to fluid flow and transmissibility. Sediments underlying the LCU were migration pathways which charged some of the largest accumulations of multiple subunconformity petroleum reservoirs on the North Slope of Alaska (Houseknecht and Bird, 2006). The LCU truncates older strata northward onto the Barrow arch and is sealed by a Cretaceous mudstone creating structural and stratigraphic traps such as the Prudhoe Bay oil field.

Brookian Sequence

The Upper Cretaceous through Tertiary Brookian sequence consists of deposits derived from the uplift and erosion of the southern Brooks Range fold and thrust belt during the Cretaceous and Tertiary. Great volumes of sediment rapidly filled the North Slope Foreland Basin and were deposited over the top of the Barrow arch, building the present continental terrace of northern Alaska (Fig. 3). This sequence consists of a distal, condensed mudstone (Hue Shale), deep marine basinal slope and outer-shelf mudstones and turbidite sandstones (Torok, Seabee, and Canning formations), and shallow marine to non-marine coal-bearing sandstones, mudstones, and conglomerates (Nanushuk, Tuluvak, Prince Creek, Schrader Bluff, and Sagavanirktok formations). Important and potential source rocks in the Brookian sequence are the organically-rich Hue Shale and the Brookian mudstones. The reservoir rocks in the Brookian are turbidites and shallow-marine to non-marine sandstones, with both structural and stratigraphic traps. The thick complex packages of siliciclastic strata of the Brookian sequence buried the underlying Ellesmerian, and Beaufortian, sequences providing the elevated temperatures needed to thermally mature the source rocks.

Chapter 3. Hydrocarbons

The American Petroleum Institute (API) gravity is the standard used to describe the specific gravity (S.G.) of crude oils. API gravity is defined as follows:

$$\text{Degrees API} = (141.5/\text{ S.G. at } 60^{o}\text{F}) - 131.5.$$

The inverse relation between API gravity and specific gravity or density allows the stems of hydrometers to be calibrated linearly (Leverson, 1956). For example, heavy oil with a density equal to water has a specific gravity of 1.0 and an API gravity of 10^{o}. Light oil with a density of 700 kg/m^3 has a specific gravity of 0.7 and an API gravity of 70.6^{o}. Most oils fall within the range of 10-70˚ API gravity. Light oil is classified by gravities above 31.1 ˚API gravity and heavy oil is classified as API gravities below 22.3˚ API. The formation of heavy oil is generally from originally lighter oil that has lost its light hydrocarbon chains due to evaporation, gravity separation, biodegradation, or water washing (Schlumberger on-line Oilfield Glossary, 2007).

Current hydrocarbon production on the North Slope is confined to the central portion of the North Slope basin. The following is a synopsis of the oil fields included in this study: Prudhoe Bay, West Sak, Kuparuk and Alpine oil fields of the Central North Slope foreland basin based on work done by Werner (1987) and Masterson (2001) (Fig. 5). Values for API gravity are from Masterson (2001).

Prudhoe Bay Field

The Prudhoe Bay oil field lies above the Barrow arch (Fig. 5) and is the most eastward field in the study area. The reservoir rock is in the Ivishak sandstone (Fig. 6) located at an average depth of 2,700 meters (8,800 feet). It is the largest oil field in the United States at approximately 48 km (30 miles) long and 16 km (10 miles) wide. Oils from the Prudhoe Bay main field area are believed to be mainly sourced from the Shublik Formation with smaller contributions from the HRZ Formation and Kingak Shale (Figs. 4, 5, 7). The average API oil gravity of the Prudhoe Bay oil field is 29˚API (Masterson, 2001). The Prudhoe Bay main field has a basal tar mat that lies at 2749 m (9020 ft) just 6-18 m (60 ft) above the oil-water contact (Wadman et al., 1979). The tar mat is geochemically similar in composition to the overlying oil column and has not been biodegraded (Masterson, 2001). It is believed to have been formed partially by gravity segregation at the base of the oil column (Masterson, 2001).

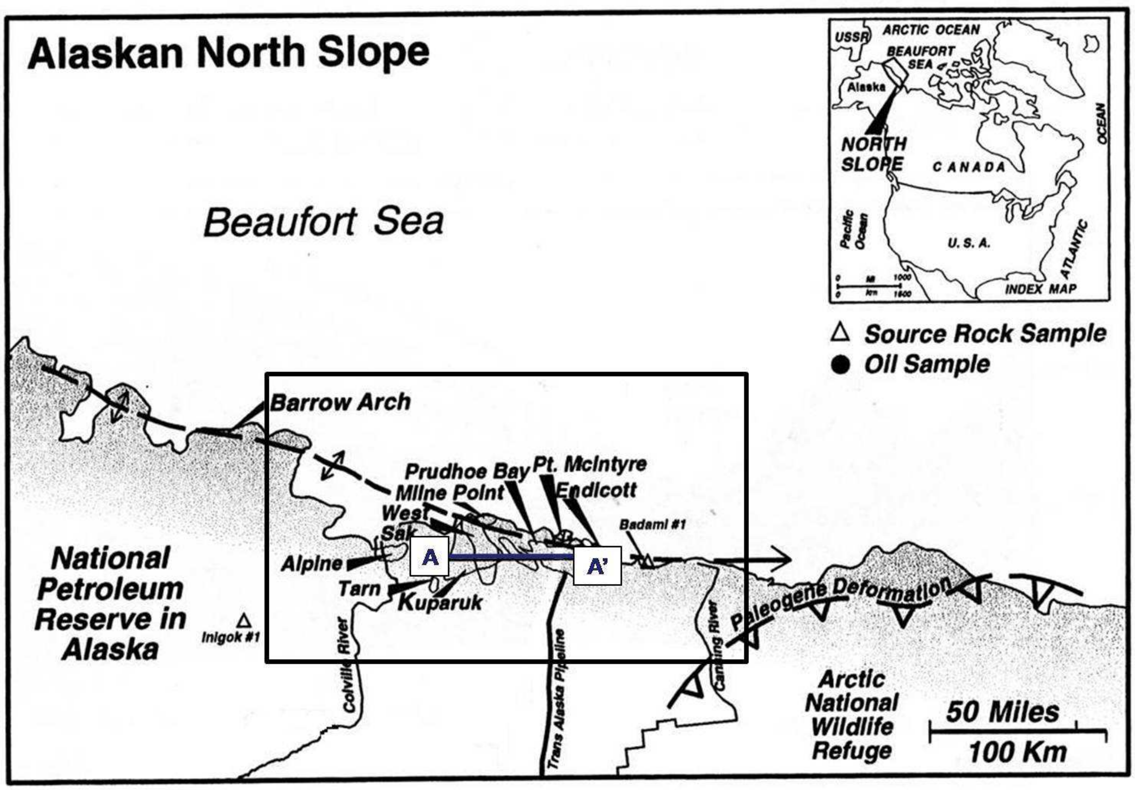


Figure 6. Current producing oil field locations within the central North Slope foreland basin with stratigraphic and structural cross-section A-A' (Fig. 7) (modified from Masterson, 2001).

Kuparuk Field

The Kuparuk reservoir is located to the west of the Prudhoe Bay Field and is structurally and stratigraphically slightly higher (Figs. 6 & 7). The reservoir sands lie above and below the LCU at approximately 1,800 m (6,000 ft) (Fig. 4, 6) and are surprisingly uniform in composition.

The reservoir sands are the Kuparuk River Formation and are divided by the LCU into an upper and lower member. The upper member is divided into the Kuparuk C and D sands and the lower member is the Kuparuk A and B sands. The major source rock is the carbonate-rich and shaley Shublik Formation. The average API oil gravity in the Kuparuk field is 23˚.

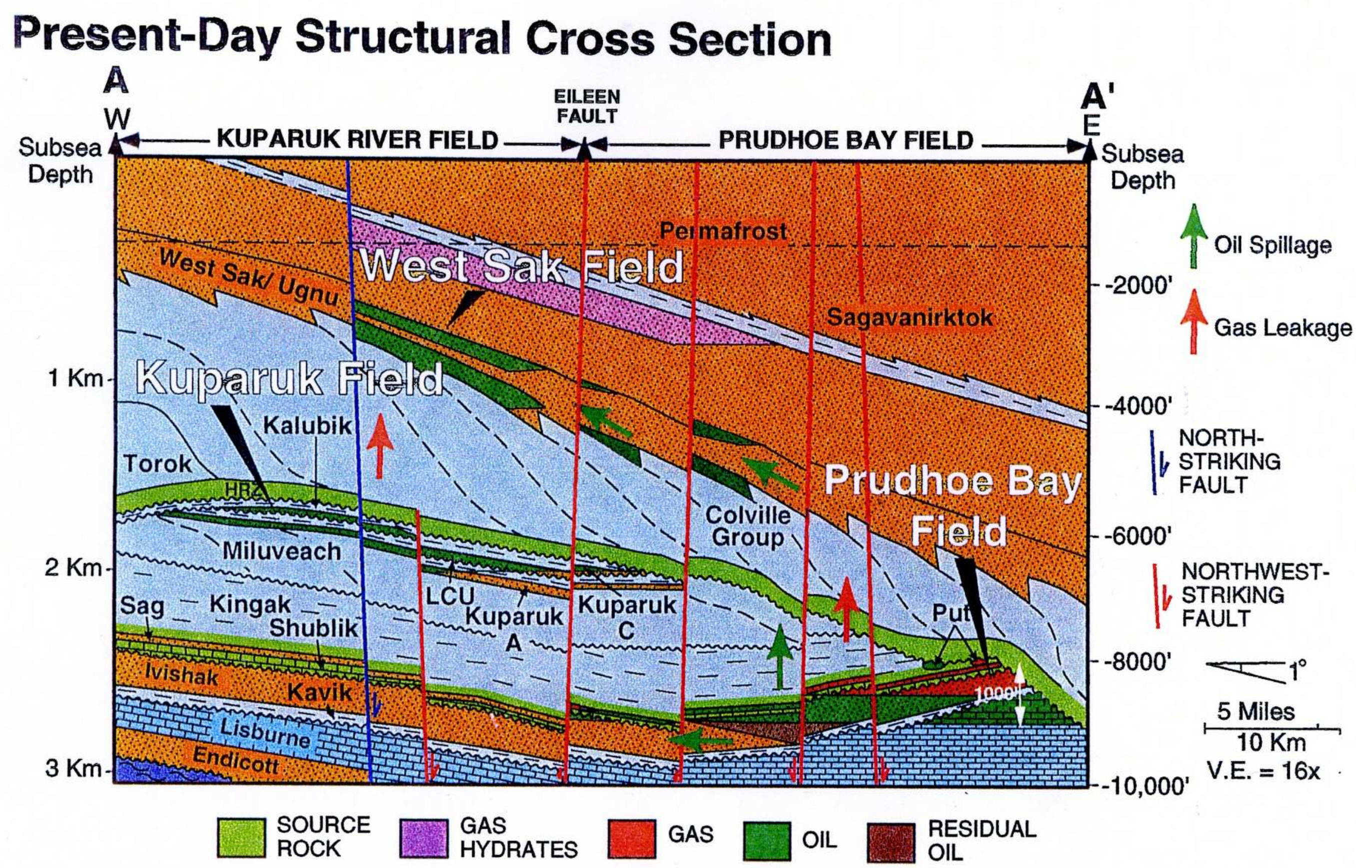


Figure 7. Stratigraphic and structural east-west cross-section A-A' from Masterson, 2001 with the locations of the Kuparuk, West Sak, and Prudhoe Bay oil field locations (From Masterson, 2001, used with permission).

West Sak

The West Sak field oils are very geochemically similar to the Prudhoe Bay field oils and are believed to have migrated 16 km (10 miles) westward and 1,500 m (5,000 ft) vertically (Fig. 6) during the Tertiary as a result of eastward tilting of the foreland basin (Masterson, 2001). The West Sak field directly overlies the Kuparuk field at depths of 1000-1,200 m (3,500-4,000 ft)

(Figs. 5 & 6), and the reservoir sands are in the Schrader Bluff Formation, which is informally referred to as the West Sak Sands (Werner, 1987). Although the West Sak oils have very similar biomarkers to the Prudhoe Bay oils, API gravity values are lower because the West Sak oils have been moderately to heavily biodegraded (Werner, 1987). The oils have a high sulfur content and API gravities ranging from 17-21˚.

Alpine Field

The Alpine oil field is the most westward field in the study area (Fig. 6). It is located at the highest structural and stratigraphic level (Figs. 4 and 6) at 2,100 m (7,000 ft). The reservoir rock is within marine sandstone that is equivalent to the eastern Kingak Shale. Alpine contains low-sulfur light oil with API gravities ranging from 35-39˚. Oils are believed to have been sourced from the Kingak shale (Fig. 4).

Chapter 4. Techniques

Spontaneous potential (SP) logs were the primary data source used to calculate pore water salinities and determine the stratigraphic distribution of sand and shale. Hydraulic heads were calculated from mud weights on the SP well log headers. Temperatures were computed from bottom hole temperatures (BHTs) on the SP log well headers. The United States Geological Survey (U.S.G.S.) provided the regional stratigraphic horizon picks for the base of permafrost and lithofacies that are publically available in the central North Slope foreland basin (Houseknecht and Bird, personal communication, 2007) as well as the base of the zone of gas hydrate stability mapped out by Collett (1998). API oil gravity values were taken from Masterson (2001), and analytical water samples of salinity (AOGCC public data) were compared to salinities estimated from SP logs.

Data Sources

There are over 6,000 public well log data files available through the Oil and Gas Conservation Commission (AOGCC) in the State of Alaska. The SP logs and water chemistry analyses used in this study were selected from this extensive data set in both paper and digital form. The U.S.G.S regional scale cross-sections (Molenaar et al., 1986, reprinted in 1988) across the North Slope basin were used as guides when selecting the location of the east-west cross-sections A-A' and C-C' (Fig. 8). The easternmost extent of previous work by Hanor et al. (2004) in the NPRA is located at the South Harrison Bay 1 well (Fig. 8) in section A-A'. Thus, this study is an eastward extension of Hanor et al. (2004) into the central part of the North Slope foreland basin.

Paul Decker (Decker, personal communication, 2006) of the Division of Oil and Gas, Alaska is constructing a Brookian coastal north-east to south-west cross-section showing the detailed regional scale stratigraphic geometries of the marine shelf clinoforms in the central North Slope. This Brookian cross-section and horizon picks from the U.S.G.S. (Houseknecht and Bird, personal communication, 2007) were used as a guide when selecting the location of the north to south B-B' cross-section (Fig.8).

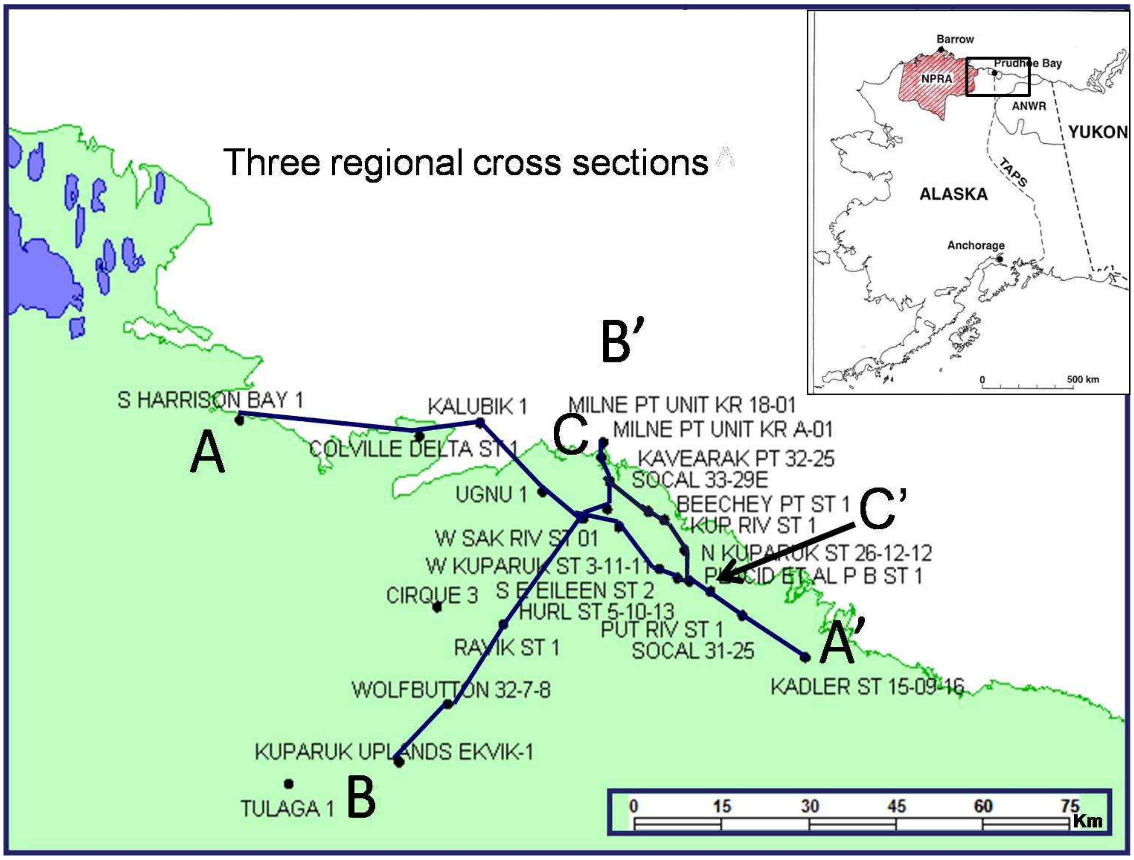


Figure 8. Three regional cross-sections A-A', B-B', and C-C' used in this study in the central North Slope foreland basin. Well locations are shown as solid circles with the well names indicated.

Lithostratigraphy

Variations in lithostratigraphy are represented by the percent of a given vertical interval occupied by sand beds. Sand bed percentages were measured on ~90 m (300 ft) vertical intervals from the SP logs. These estimates can be potentially used on a regional scale for determining the lateral connectivity of large sandy sequences and for correlation of large shaley aquitards.

Salinity Calculations

Formation water salinity was calculated from SP logs based on the Bateman and Konen (1977) algorithm, with corrections for temperature. Locations of the 24 wells used for calculating formation water salinity are shown on Figure 8. The deepest well penetration reached a depth of 4,465 m (14,650 ft). The SP log was the preferred method for calculating salinity, because an SP log was available in every well selected in the cross-sections.

Paper blue line duplications of the SP logs were used to take measurements. First, the shale base line was drawn as a base for measuring the SP log deflection in millivolts (Fig. 9). These measurements as well as the highlighted information recorded from the well header (Fig. 10). were then entered into a Visual Basic for Applications (VBA) program in Microsoft Excel developed by Hanor (personal communication, 2007) to calculate total dissolved solids (TDS) from the algorithm of Batemen and Konen (1977). This program does not correct for bed thickness, so thin sands that are less than 30 ft thick or highly resistive beds yield lower than true salinity (Funayama, 1990). The program calculates salinity in ppm, temperature (C˚), pressure, and fresh-water equivalent hydraulic heads (m) from the SP deflection and mud weight information derived from the well headers. Inaccuracies from well header notes associated with SP logs analysis in the Arctic include: bad ground connections and the arctic environment with permafrost interfered in some wells with controlling SP wander (Woodward, 1987).

Temperatures

Temperatures were estimated from bottom hole temperatures (BHTs) recorded on the well headers using the correction scheme of Kehle (1971). This correction was originally derived for Gulf Coast wells, but it should compensate for some of the cooling effects on the formation induced by circulation of surface temperature mud in North Slope wells.

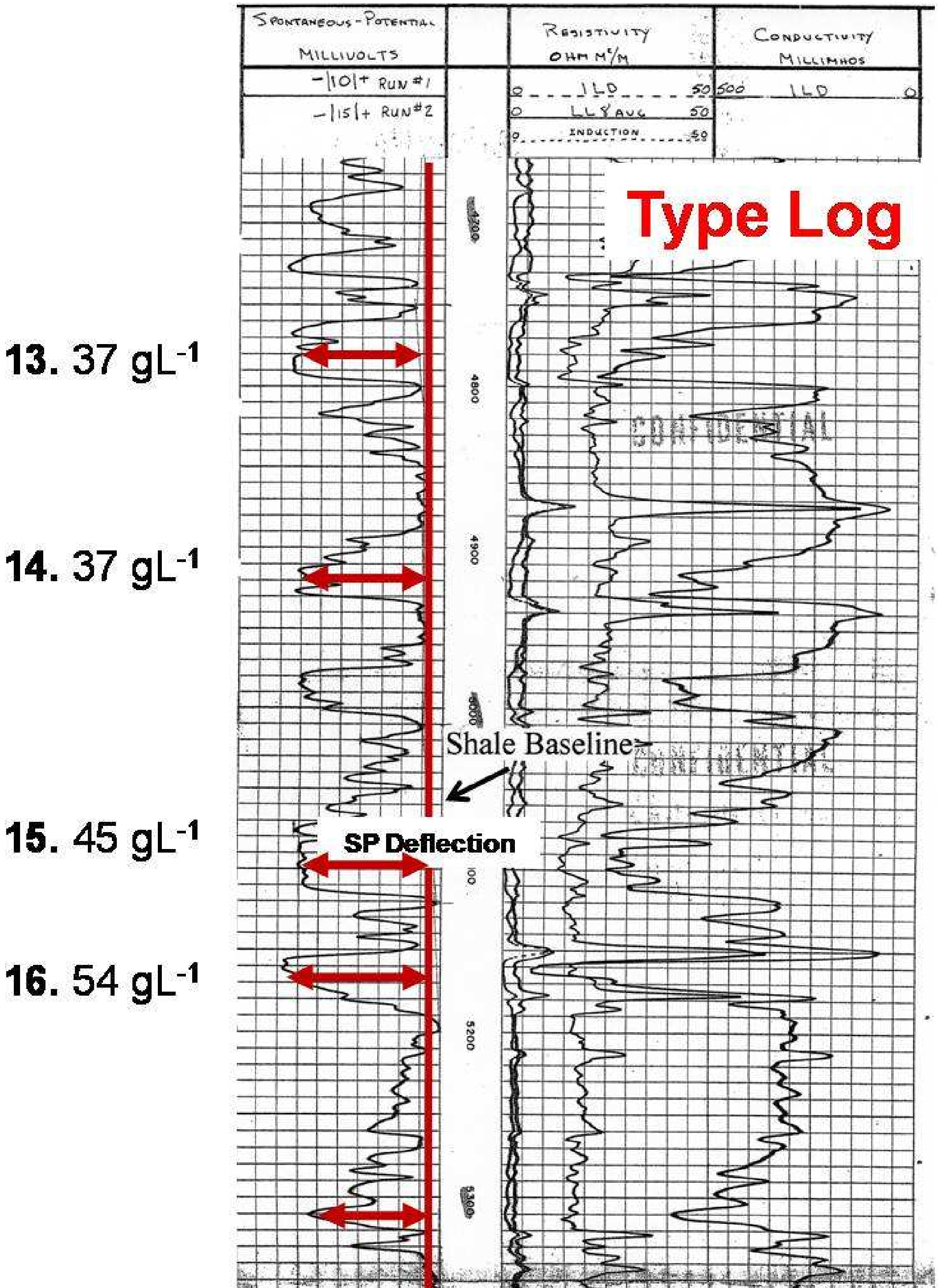
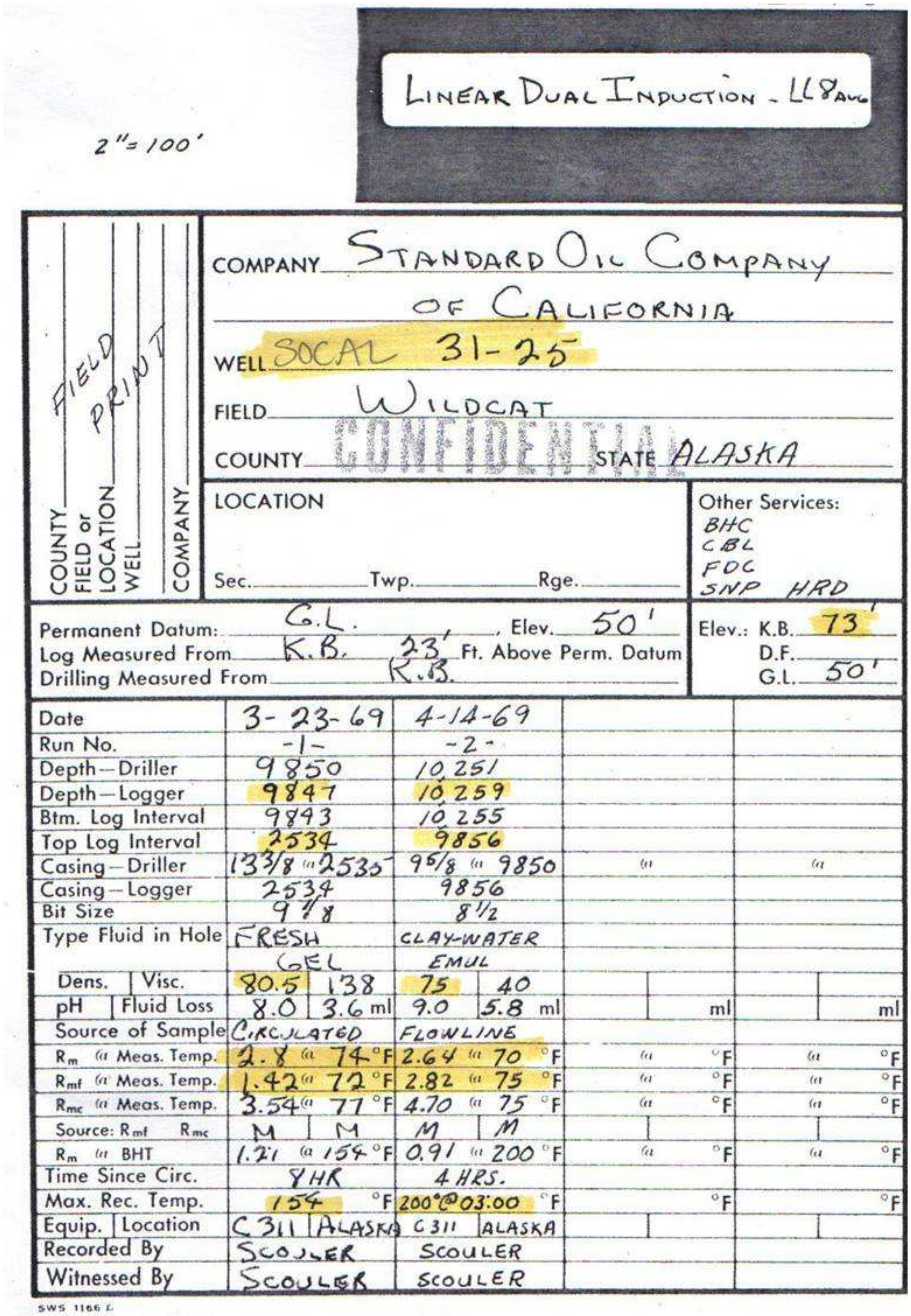


Figure 9. Type SP log is from the no longer confidential Socal 31-25 well with data collection points 13-16 and their equivalent calculated salinity values in gL^{-1} with the shale baseline and SP deflection indicated in red.



2" = 100'

LINEAR DUAL INDUCTION - LL8 AVG

FIELD PRINT

COUNTY / FIELD or LOCATION / WELL / COMPANY

COMPANY STANDARD OIL COMPANY OF CALIFORNIA

WELL SOCAL 31-25

FIELD WILDCAT

COUNTY CONFIDENTIAL STATE ALASKA

LOCATION

Sec. Twp. Rge.

Other Services: BHC CBL FDC SNP HRD

Permanent Datum: G.L., Elev. 50'

Log Measured From K.B. 23' Ft. Above Perm. Datum

Drilling Measured From K.B.

Elev.: K.B. 73' D.F. G.L. 50'

Date	3-23-69	4-14-69		
Run No.	-1-	-2-		
Depth—Driller	9850	10,251		
Depth—Logger	9847	10,259		
Btm. Log Interval	9843	10,255		
Top Log Interval	2534	9856		
Casing—Driller	13 3/8 @ 2535	9 5/8 @ 9850	@	@
Casing—Logger	2534	9856		
Bit Size	9 7/8	8 1/2		
Type Fluid in Hole	FRESH GEL	CLAY-WATER EMUL		
Dens. | Visc.	80.5 | 38	75 | 40	|	|
pH | Fluid Loss	8.0 | 3.6 ml	9.0 | 5.8 ml	| ml	| ml
Source of Sample	CIRCULATED	FLOWLINE		
R_m @ Meas. Temp.	2.8 @ 74 °F	2.64 @ 70 °F	@ °F	@ °F
R_{mf} @ Meas. Temp.	1.42 @ 72 °F	2.82 @ 75 °F	@ °F	@ °F
R_{mc} @ Meas. Temp.	3.54 @ 77 °F	4.70 @ 75 °F	@ °F	@ °F
Source: R_{mf} R_{mc}	M | M	M | M	|	|
R_m @ BHT	1.21 @ 154 °F	0.91 @ 200 °F	@ °F	@ °F
Time Since Circ.	8 HR	4 HRS.		
Max. Rec. Temp.	154 °F	200°@03:00 °F	°F	°F
Equip. | Location	C311 | ALASKA	C311 | ALASKA	|	|
Recorded By	SCOULER	SCOULER		
Witnessed By	SCOULER	SCOULER		

SWS 1166 E

Figure 10. Example of the well header information used for salinity calculations, hydraulic heads, and temperature as indicated by yellow highlights in the Socal 21-35 type log.

Water Analyses

Analyses of produced waters were available through the AOGCC for the Prudhoe Bay field Sohio water well, the Milne Point Unit, B-1 water well, the A-1 Canning River Unit (Southeast Kavik Prospect), the Colville River Delta boring A, and for the Kuparuk and Ugnu formations. Salinity from water analysis reports were compared to the calculated SP salinity to check for accuracy.

Hydraulic Heads

Following Hanor et al. (2004) fresh-water equivalent hydraulic heads are calculated from mud weights recorded on the well headers, by the following equation:

$$h_{fw} = = (P/(\rho_{fw} \text{ x } g)) + z$$

where P is fluid pressure, ρ_{fw} is the density of fresh water, g is the gravitational constant, and z is elevation. P is calculated from mud weights and depths reported on the log headers. Drilling fluids are typically overweighted to prevent well blow-out, and the pressures calculated here may thus be slightly in excess of true fluid pressures. The density of fresh water was taken to be 1000 kg m^{-3}. Daily drilling mud records would yield more a more detailed picture of variations in hydraulic heads.

Well Picks

Well picks (formation tops or horizons) were provided in a Microsoft Excel spreadsheet by the U.S.G.S. (Dave Houseknecht, personal communication). The major Ellesmerian, Beaufortian, and Brookian sequences, unconformities and permafrost extent were the main picks used in this study to look for correlations between fluid flow, as inferred from variations in salinity, temperature, and hydraulic head, and changes in lithology that might represent either barriers or conduits for fluid flow.

Surfer Visualization

Surfer 7.0 (Golden Software) was used to construct subsurface contour cross-sections of sand content, salinity, temperature, and pressure with the correct well spacing. The radial basis gridding algorithm with a maximum value of anisotropy of 10 on the horizontal axis was used to more accurately represent lateral connectivity of the sedimentary facies. Post maps have been overlain on all of the Surfer subsurface visualizations with small black ticks representing data measurement points.

Workstation Visualization

Digital SP and Gamma Ray (GR) log curves were loaded onto a Linux workstation in LSU's subsurface lab. The subsurface program used was Landmark Stratworks. The files were converted into the LAS (log ASCII standard) file format, which included the available curves for each well. The digital data were obtained from the AOGCC in Anchorage, Alaska. A screen shot of representative SP and GR logs curves is shown in Figure 11.

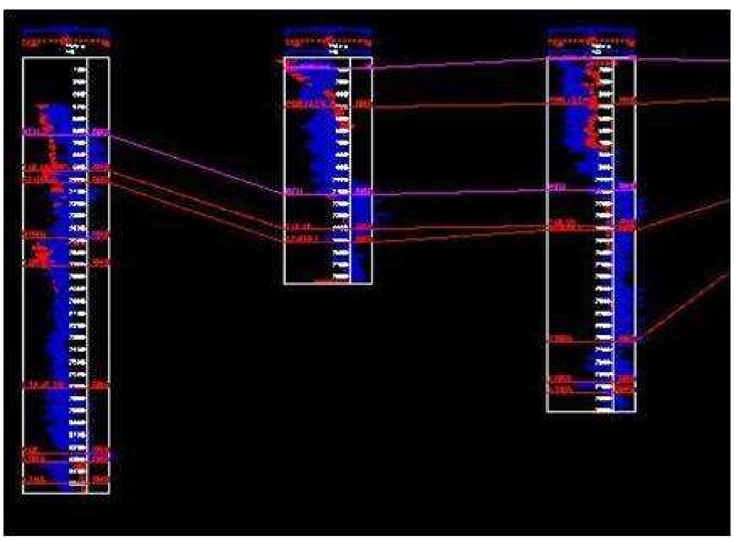


Figure 11. Screen shot of three wells from Landmark Stratworks subsurface program with the SP log represented in red, the GR log represented in blue and the horizon picks represented in red and pink horizontal straight lines. It was not possible to obtain a sharper image resolution screenshot.

Chapter 5. Results

Sand bed lithostratigraphy, salinity, temperature, depth to base of permafrost and the data control locations for some of the North Slope oil fields are plotted on cross-sections A-A', B-B', and C-C'. The data used to make these sections is given in Appendix A. Sections A-A' and C-C' are roughly parallel to the coast and B-B' is approximately perpendicular to the coast and the other two cross-sections. The cross tie well between sections A-A' and B-B' is the West Sak well and the cross-tie well between C-C' and B-B' is the Kavearak Point (Kav. Pt.) well.

Lithostratigraphy

Results of the estimates of the distribution of sandy and shaley intervals are reported in Appendix A. The upper portion of the west to east section A-A' (Fig. 12) is dominated by sand to depths of a few hundred meters to 1 km. This interval thickens to the east and corresponds to late Cretaceous and Cenozoic marine shelf and non-marine sediments. The sandy interval is underlain by a shaley interval 1 to 2 km in thickness which represents the Triassic through early Cretaceous marine slope and basin sediments of the Beaufortian sequence (Fig. 4). This interval thins to the east. The shaley interval is underlain by sandy sediments of the Ellesmerian megasequence (Fig. 4).

The B-B' southwest to northeast cross-section (Fig. 13) has areas of laterally continuous sandy and shaley intervals. The thick shale interval shown in the south-western side end of the B-B' section at the Kuparuk Ekvik well is an artifact of plotting by the Surfer program. There are however, relatively thin shale beds present through the mid-section of the B-B' section at depths of 2 km. There is insufficient well coverage to determine the continuity of these thin shale beds. The section is sand-dominated above and below the shale interval.

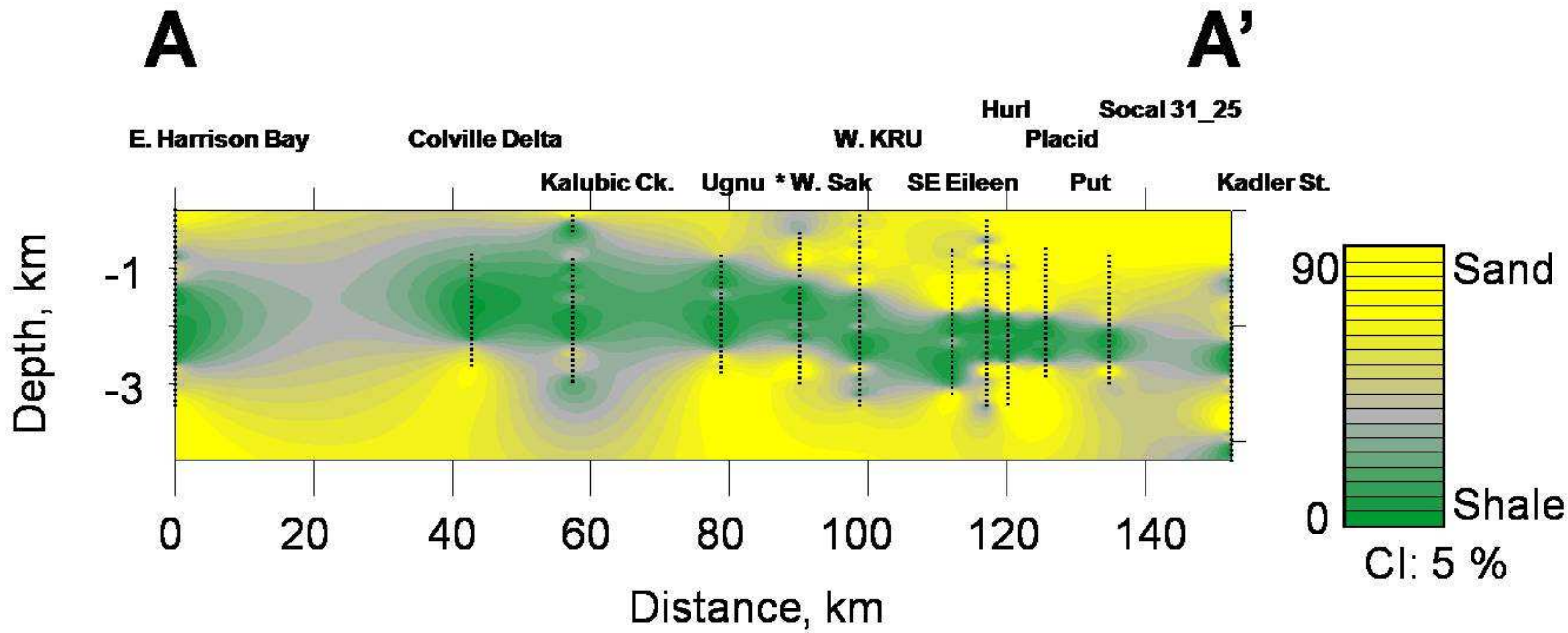


Figure 12. Variation in percent sand beds in 300 feet (100 m) vertical intervals for the coastal northwest-southeast cross-section A-A' (see Fig. 7 for profile location). Yellow represents sand dominated intervals and green represents shale dominated intervals. The black dots show vertical control for each well. Contours above and below the vertical control in each well are in part artifacts of contouring and should be ignored on this and on the subsequent cross sections.

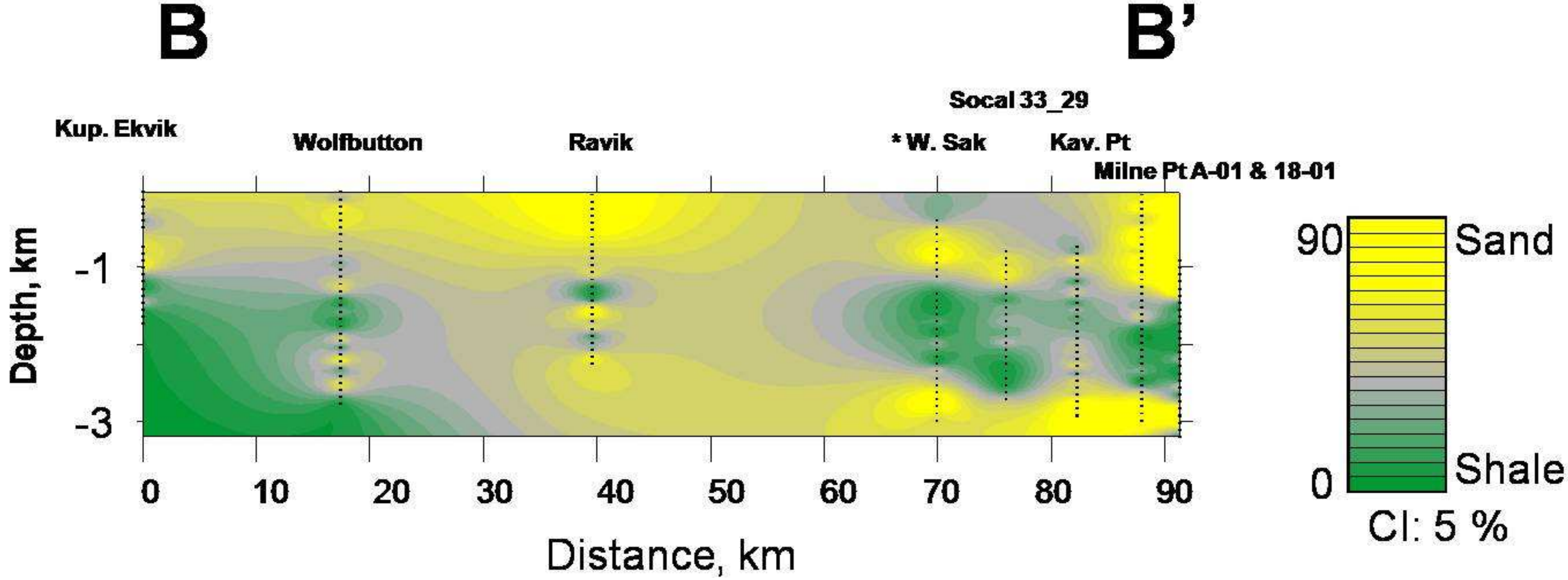


Figure 13. Variation in percent sand beds in 300 feet (100 m) vertical intervals for the south-west to north-east cross-section B-B' (see Fig. 7 for profile location). Yellow represents sand dominated intervals and green represents shale dominated intervals.

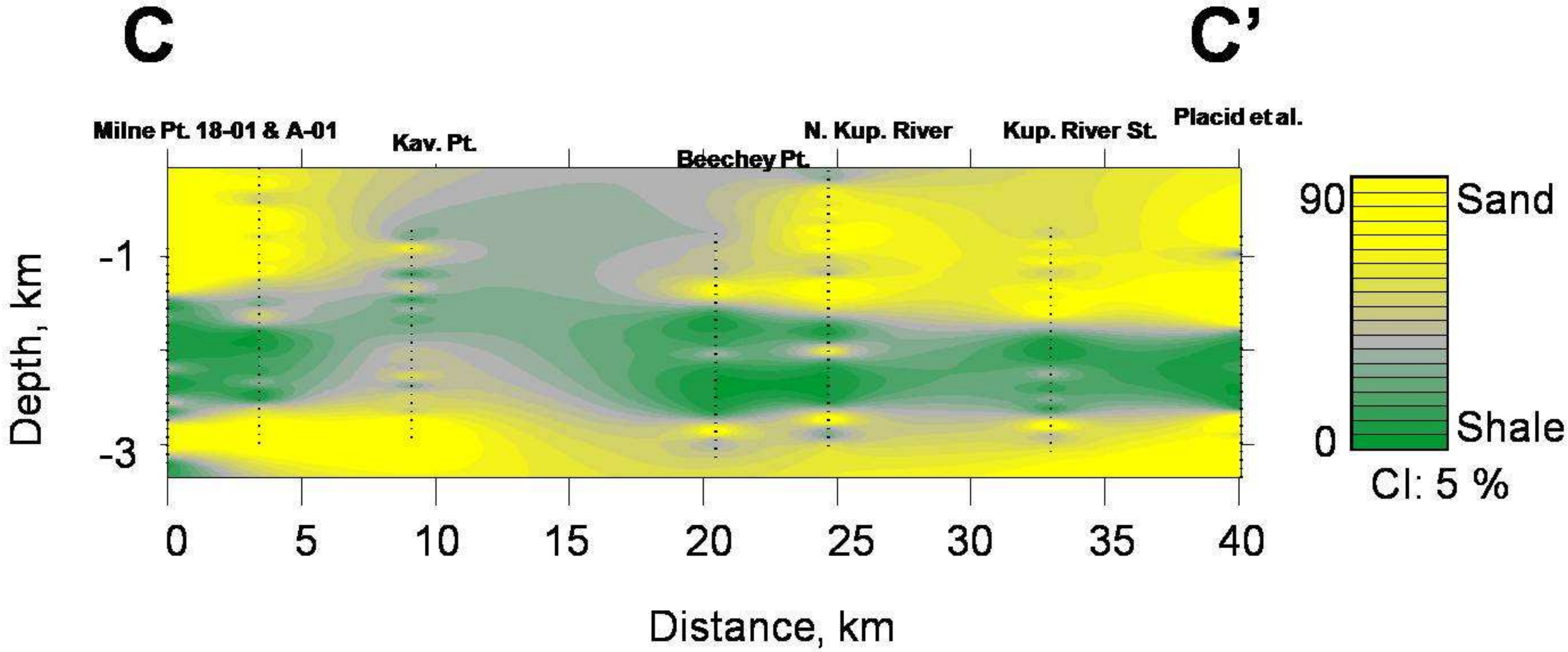


Figure 14. Variation in percent sand beds in 300 feet (100 m) vertical intervals for the most coastal north-southeast cross-section C-C' (see Fig. 7 for profile location). Yellow represents sand dominated intervals and green represents shale dominated intervals.

The C-C' north to southeast cross-section (Fig. 14) is the closest section to the northern coast of Alaska and has a similar shale and sand distribution as the neighboring cross-section A-A' to the south. There is a thick shaley interval located between depths of 1.5-2.5 km depth with sand above and below. The shaley interval changes dip between the Kaverak Point and Beechey Point wells, which could reflect the presence of the Barrow Arch (Fig. 2).

Salinity

Most of the sedimentary rocks of the central North Slope foreland basin, until the Upper Cretaceous, were deposited in a marine environment and had initial pore-water salinities (connate salinities) equivalent to normal seawater salinity (35gL^{-1}) (Fig. 4). Rocks younger than the Upper Cretaceous are mainly composed of non-marine rocks (Fig. 4). The calculated salinities from SP logs ranged from fresh (< 35 gL^{-1}), to seawater salinities (35 gL^{-1}), to hypersaline (> 35 gL^{-1}), with the highest salinity encountered at 60 gL^{-1}. The Surfer subsurface profiles are a visual representation of the salinity variations encountered in all three cross-sections (Figs. 15-17).

The salinity cross section A-A' (Fig. 15) is an eastward extension of the previous work done by Hanor et al., 2004 and is located parallel to the northern coast of Alaska. It is the longest cross-section in this study and starts with the South Harrison Bay well on the western edge of the section. Hypersaline waters (yellow) were encountered at depths below 3 km at South Harrison Bay and also between depths of 2.3-2.5 km at the Socal 31-25 well. Above and below the hypersaline waters are areas of sea-water salinity (red) and slightly lower salinities (purple). Much fresher waters (blue) are present throughout much of the section from the surface to depths greater than 3 km depth.

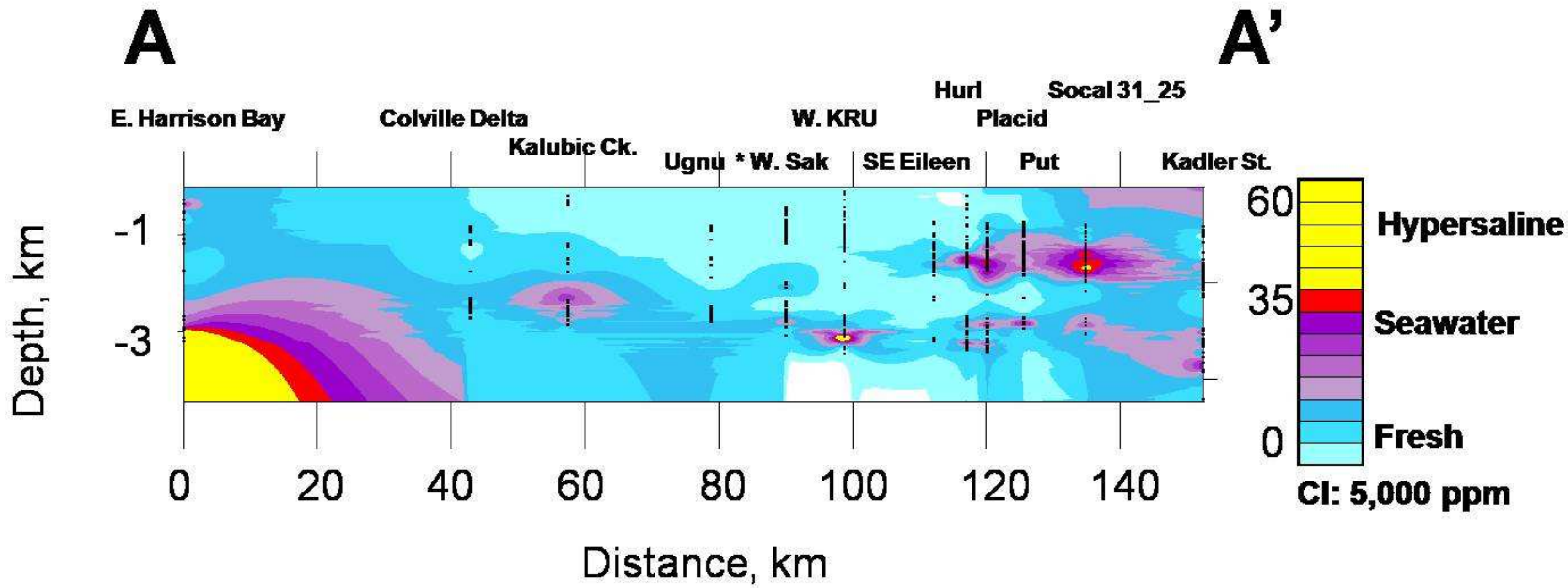


Figure 15. Spatial variations of salinity in the northwest-southeast coastal A-A' cross-section (Fig. 7 for profile location) showing fresh water in blue, seawater in red, and hypersaline water in yellow. Contour interval is 5,000 ppm or 5 gL^{-1}.

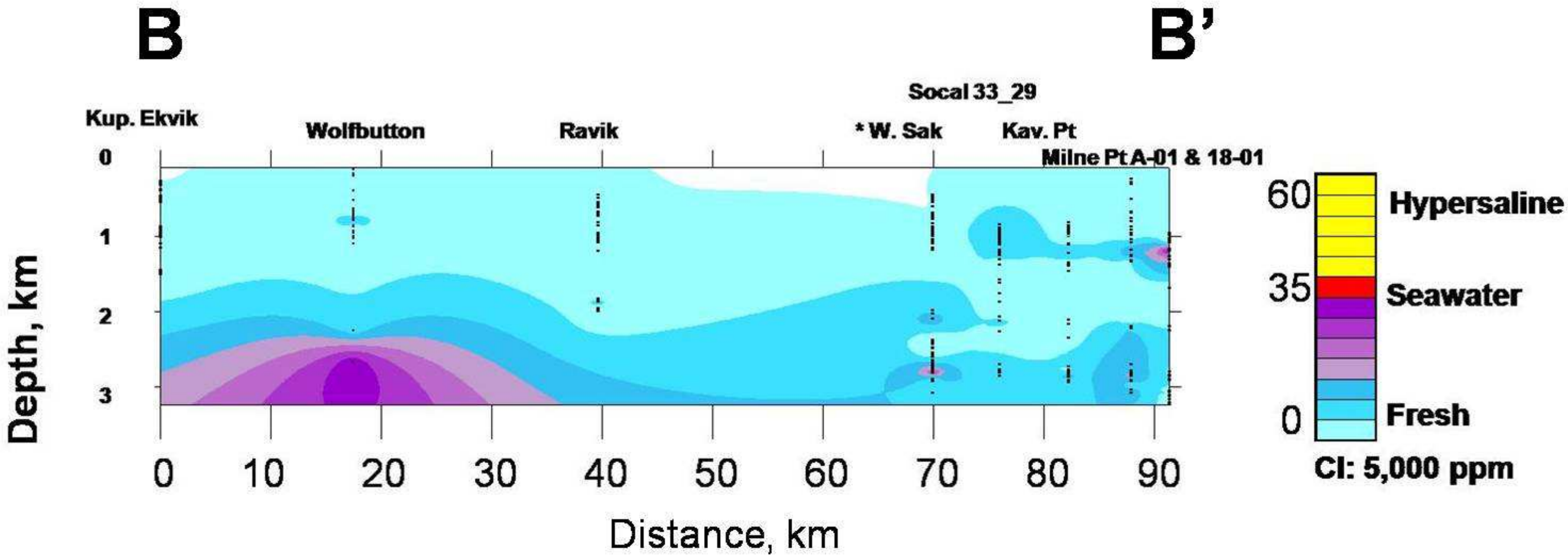


Figure 16. Spatial variations in the salinity of the south-west to north-east B-B' cross-section (Fig. 7 for profile location) with fresh water represented in blue and water approaching seawater salinities in purple. B-B' doesn't intersect waters equivalent to seawater salinities or hypersaline waters. Contour interval is 5,000 ppm or 5 gL^{-1}.

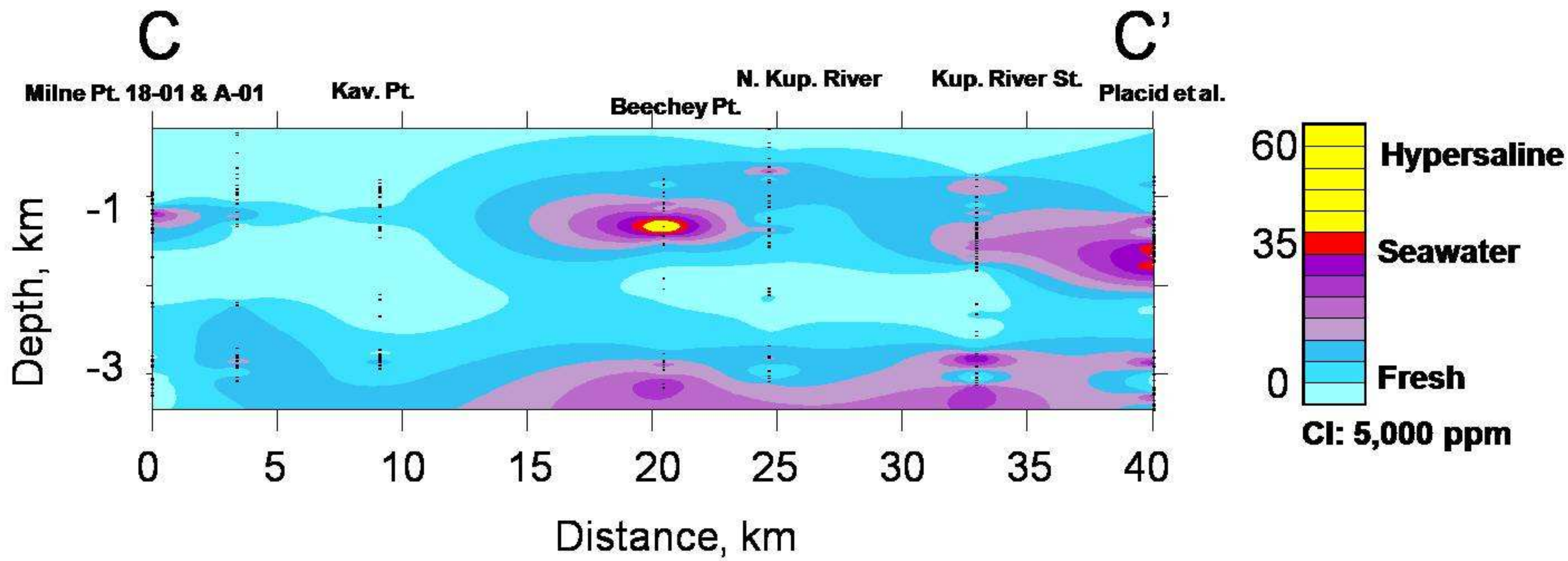


Figure 17. Spatial variations of salinity of the most coastal north- southeast C-C' cross-section (Fig. 7 for profile location) showing fresh water in blue, seawater in red, and hypersaline water in yellow. Contour interval is 5,000 ppm or 5 gL^{-1}.

The salinities of waters in section B-B' are all less than that of seawater. However, a few data points from the Wolfbutton and West Sak well approach seawater (purple) salinity at depth of approximately 3 km, but spatial control is limited. The Milne Point 18-01 well encountered saltier water at depths of 1 to 1.4 km.

Hypersaline waters were found in section C-C' at depths of 1 to 1.6 km at the Beechey Point well in the center of the section (Fig. 17). The seawater salinities that were encountered at depths of approximately 1.2 to 1.7 km at the far southeast end of the C-C' section at the Placid et al. well.

There are three possible correlative horizons of salty water in the C-C' cross-section: one at a depth of approximately 1 km to the north at the Milne Pt. 18-01 well, and a second at a depth of approximately 1.6 to 2 km at the Placid et al. There is a third deeper saline horizon, which is more extensive and correlative and is located at depths greater than3 km depth. The deeper horizon stretches beneath the Beechey Point well in the center of the C-C' section to the southeastern edge end of the section at the Placid et. al well and consists of waters having salinities just slightly less than that of seawater.

Temperature

Temperature results estimated from BHTs are shown for all three subsurface cross-sections (Figs. 18-20). The highest temperatures encountered from well log headers bottom hole temperature (BHT) readings are in the A-A' east-west coastal cross-section, (Fig. 18) and range from 7-203˚C. The highest temperature gradient of this section occurs at depths of approximately 3 km on the northwestern side of A-A' cross-section beneath the Colville Delta well. The highest temperatures at any given depth in the section B-B' range from ~15-125˚ at the West Sak and Kavearak Point wells at ~3 km depth on the northeastern end of the section. The

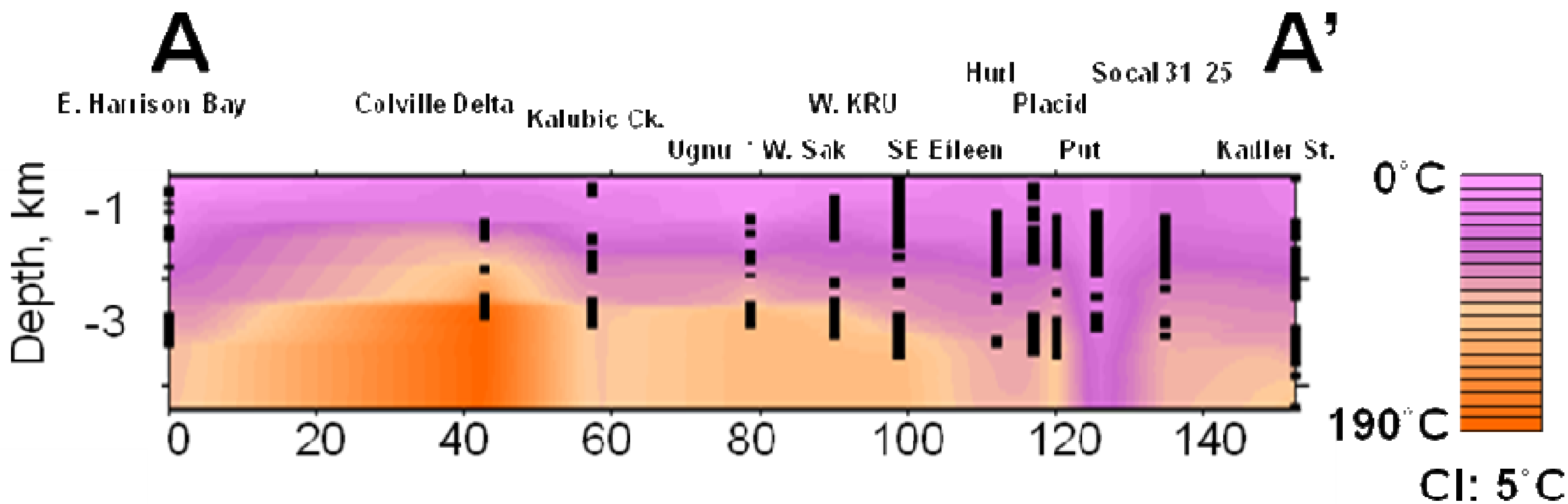


Figure 18. Spatial variations in subsurface temperature (˚C) patterns derived from bottom hole temperatures (BHT) from well headers in the coastal northwest-southeast A-A’ (see Fig. 7 for cross-section location) cross-section.

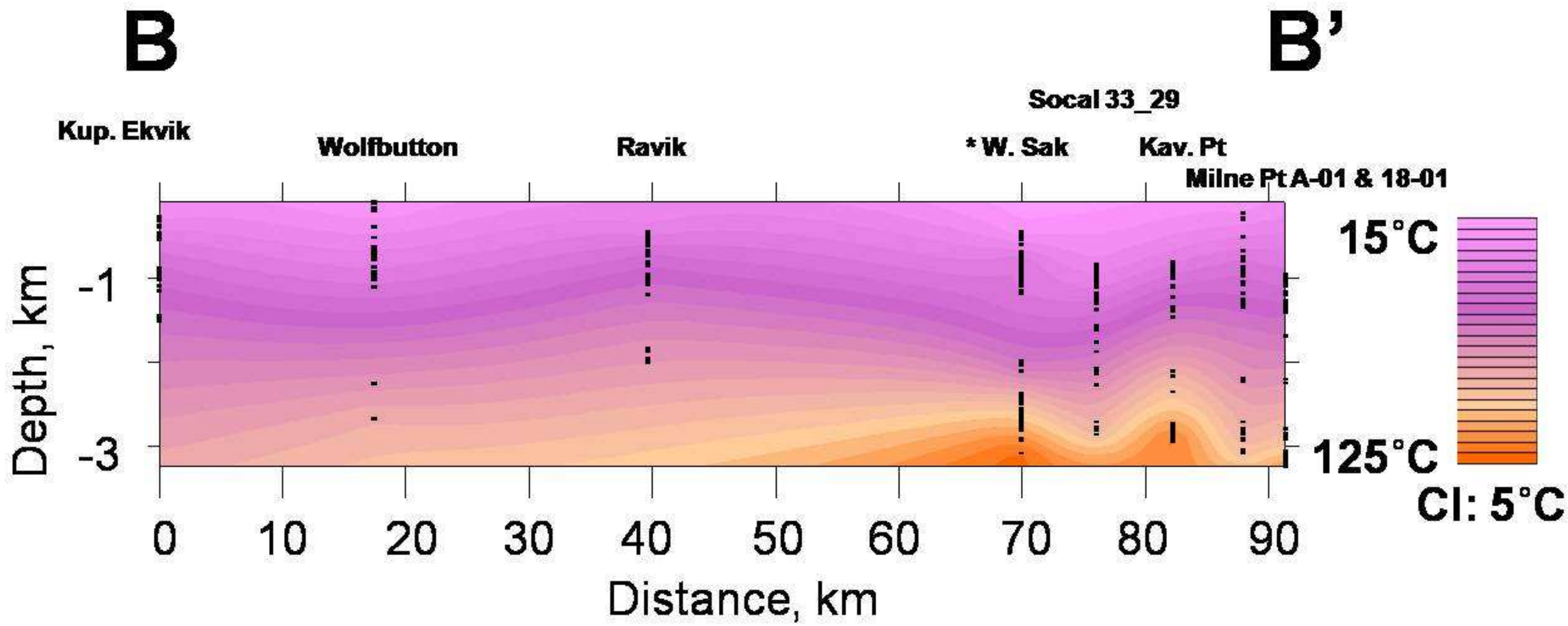


Figure 19. Spatial variations in subsurface temperature (˚C) patterns derived from BHT from well headers in the south-west to north-east B-B' (see Fig. 7 for cross-section location) cross- section.

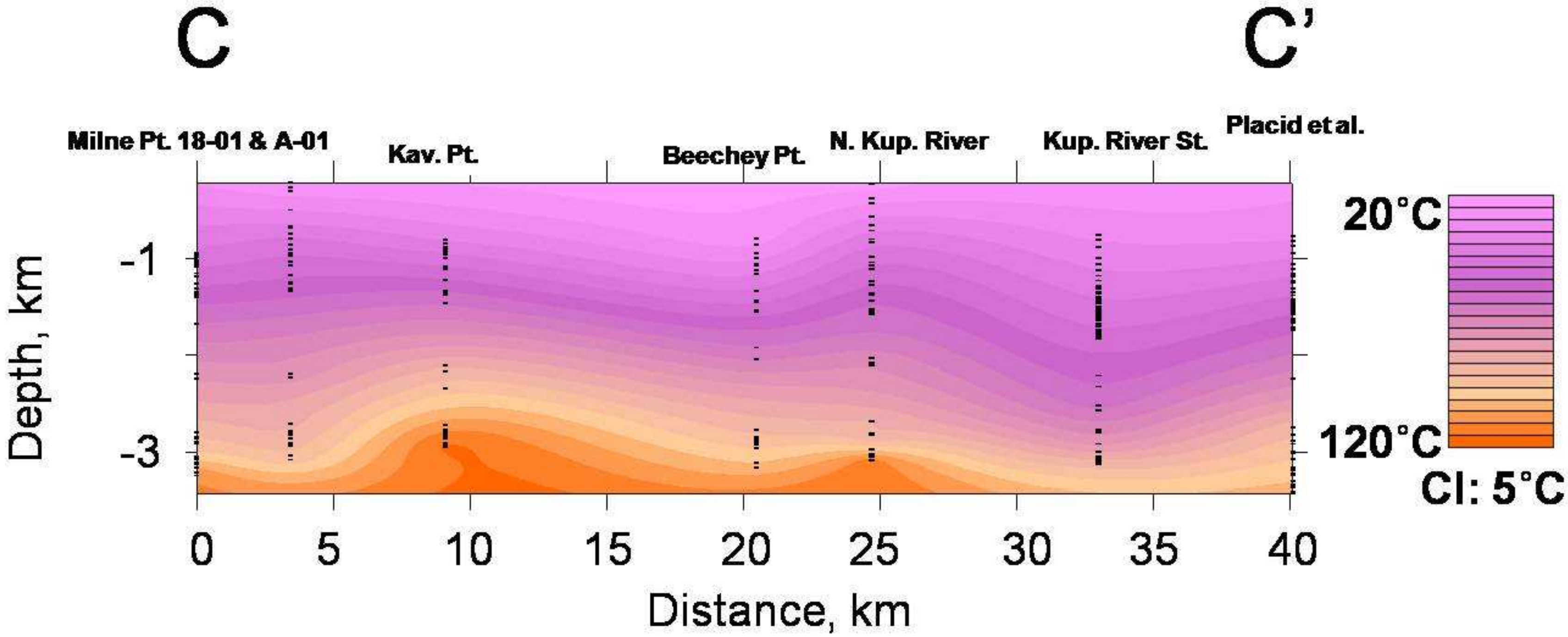


Figure 20. Spatial variations in subsurface temperature (˚C) patterns derived from BHT from well headers in the north to south-west C-C' (see Fig. 7 for cross-section location) cross-section.

calculated temperatures in section C-C' range from approximately 20 to 120˚C. The temperature gradient was the steepest at the Kavearak Point and North Kuparuk wells and their temperatures correlate between these wells in the north and central areas of the cross-section. Note that the temperature scale for section A-A' differs from the scale for B-B' and C-C'. The corrected BHT for the bottom of the Colville Delta well in section A-A' is 190^{o}C, which seems erroneously high and should thus be used with caution. This temperature reflects a possible error in the uncorrected BHT recorded on the log header for this well.

Water Analyses

The salinities from the public water analysis (AOGCC) for 8 water wells range from 0.786-60.217 gL^{-1}. The waters have high levels of bicarbonate which range from 0.176-3.560 gL^{-1}.

Hydraulic Head

Fresh water equivalent hydraulic heads were calculated and contoured at a depth of 1 km depth (Fig. 21). There is an area of low head at the West Kuparuk and SE Eileen wells (Fig. 21) near the coast.

Oil Fields and API Oil Gravity

Salinity surfer plots were overlain with the location of North Slope oil fields to examine for a possible correlation between salinity and oil field API gravity (Figs. 22, 23, 24). The subsurface oil field locations and the API gravities of the oils are from Masterson (2001).

The Prudhoe Bay oil field (Figs. 1, 5) was plotted on the A-A' and B-B' salinity Surfer cross sections (Figs. 22, 23) from the W. KRU, SE Eileen, Hurl, and Kavearak

Point (Kav. Pt.) wells. The Prudhoe Bay oil field sample was taken at depths of 2.6-2.7 km with API oil gravities ranging from 22-36˚. The Kuparuk oil field (Figs. 1, 5) was plotted on the east-west A-A' salinity Surfer profile (Fig. 22) from the Kalubic Ck. well intersection sampled at a depth of 1.9 km with API oil gravities of 26˚. The West Sak oil field (Figs. 1, 5) was plotted on the A-A' salinity Surfer profile (Fig. 22) from the West Sak (W.Sak) well at a depths of 1.0-1.1 km with API oil gravities ranging from 17-21˚. Another unnamed oil field sample was taken from the Kavearak Pt. well intersected in the B-B' and C-C salinity Surfer profiles (Figs. 23, 24) from Jurassic age sand at a depth of 2.3 km with an API oil gravity of 36˚.

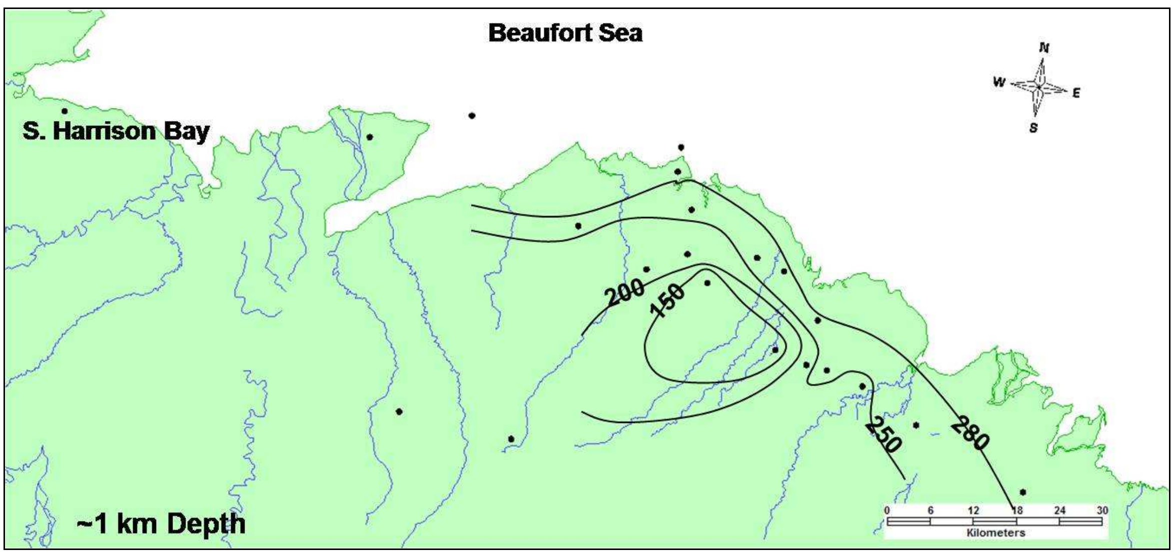


Figure 21. Contour map of hydraulic head calculated from well headers from 1 km in depth with wells shown as black points.

Permafrost

A combination of two sources (Collett and others, 1989, and Decker, in progress) were used to map out the extent and overlay the depth to the base of permafrost onto the temperature profiles to look for possible correlations between elevated temperatures and shallower permafrost for the B-B' and C-C' cross-sections of this study (Figs. 25, 26).

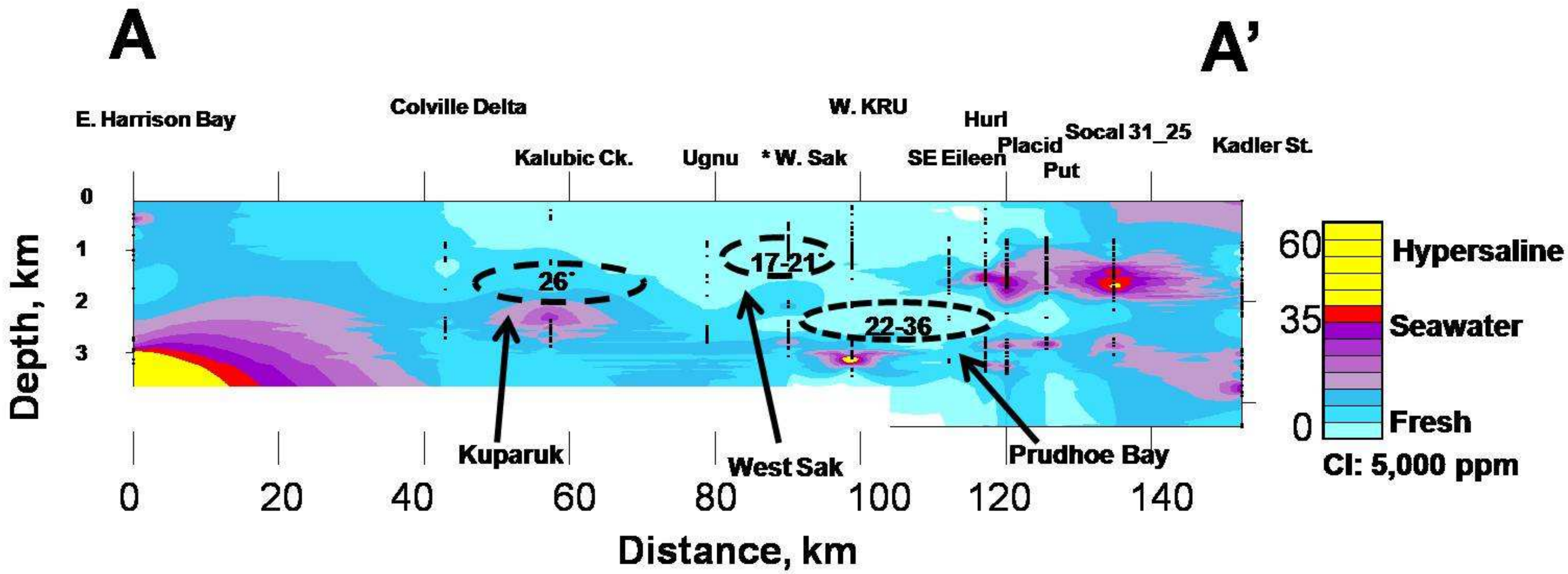


Figure 22. Spatial variations in salinity in cross-section A-A' overlain with the Kuparuk, West Sak, and Prudhoe Bay oil fields and the fields corresponding API oil gravities.

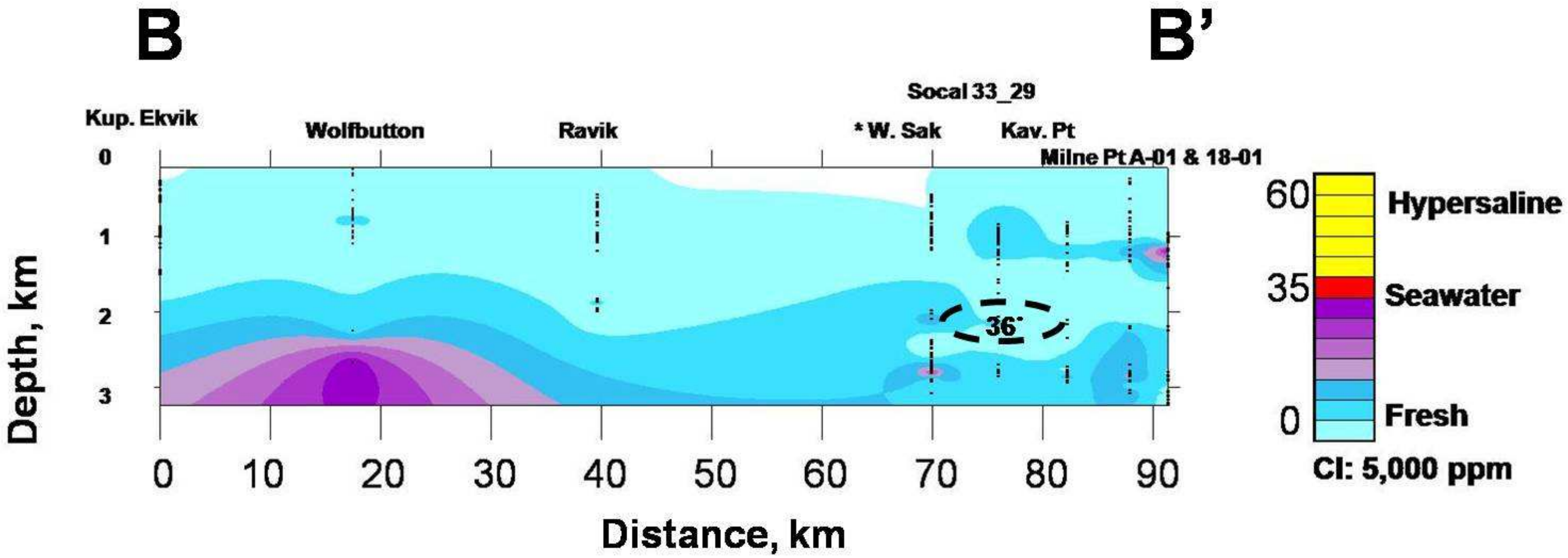


Figure 23. Spatial variations in salinity in cross-section B-B' overlain with the Prudhoe Bay oil fields and another unnamed oil sample and the fields corresponding API oil gravities.

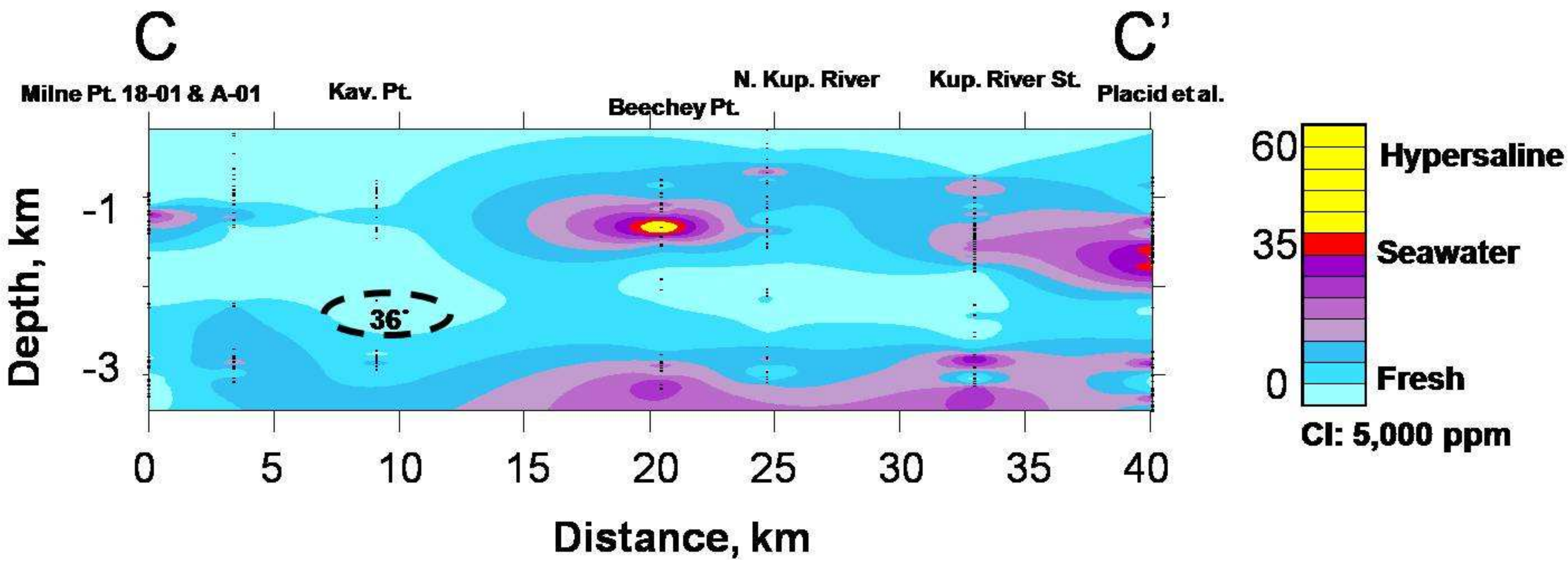


Figure 24. Spatial variations in salinity in cross-section profile C-C' overlain with an unnamed oil sample with the corresponding API oil gravity.

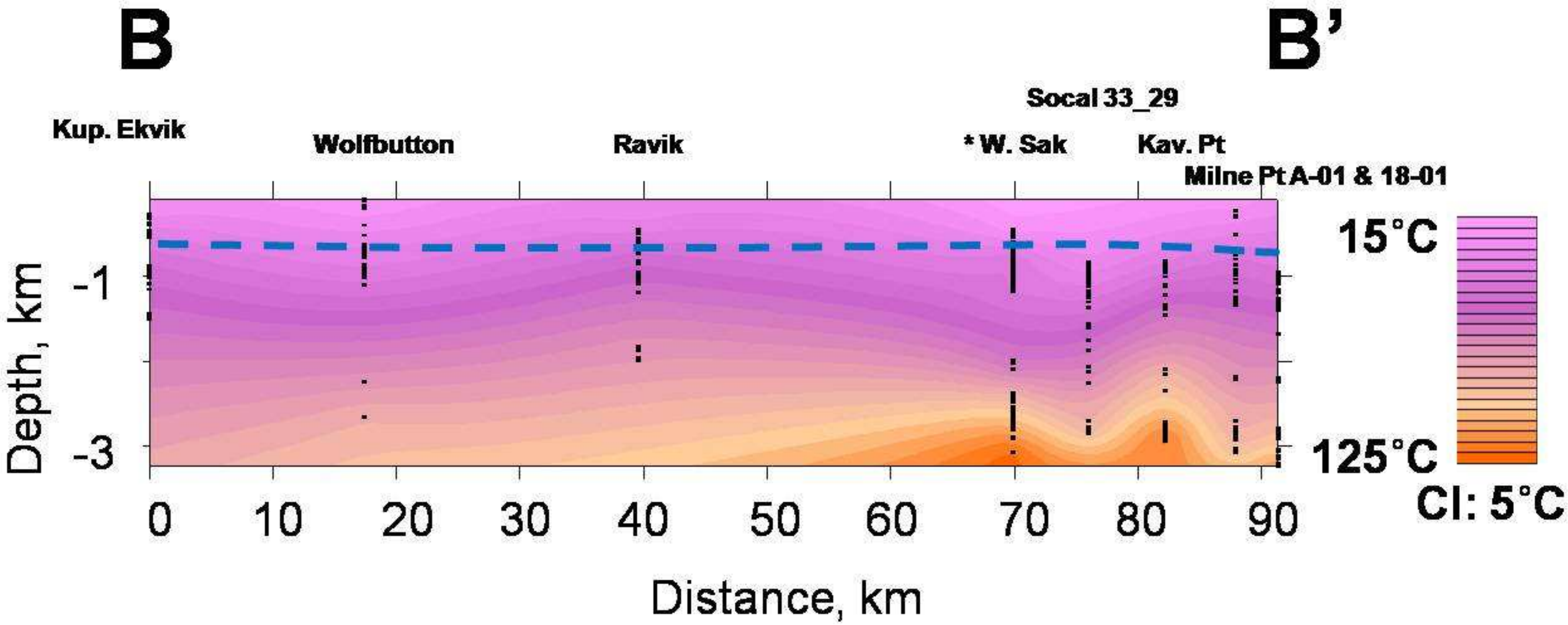


Figure 25. Spatial variations in subsurface temperature (˚C) patterns derived from BHT for the B-B' cross-section with the extent of permafrost overlain and shown by a blue dotted line.

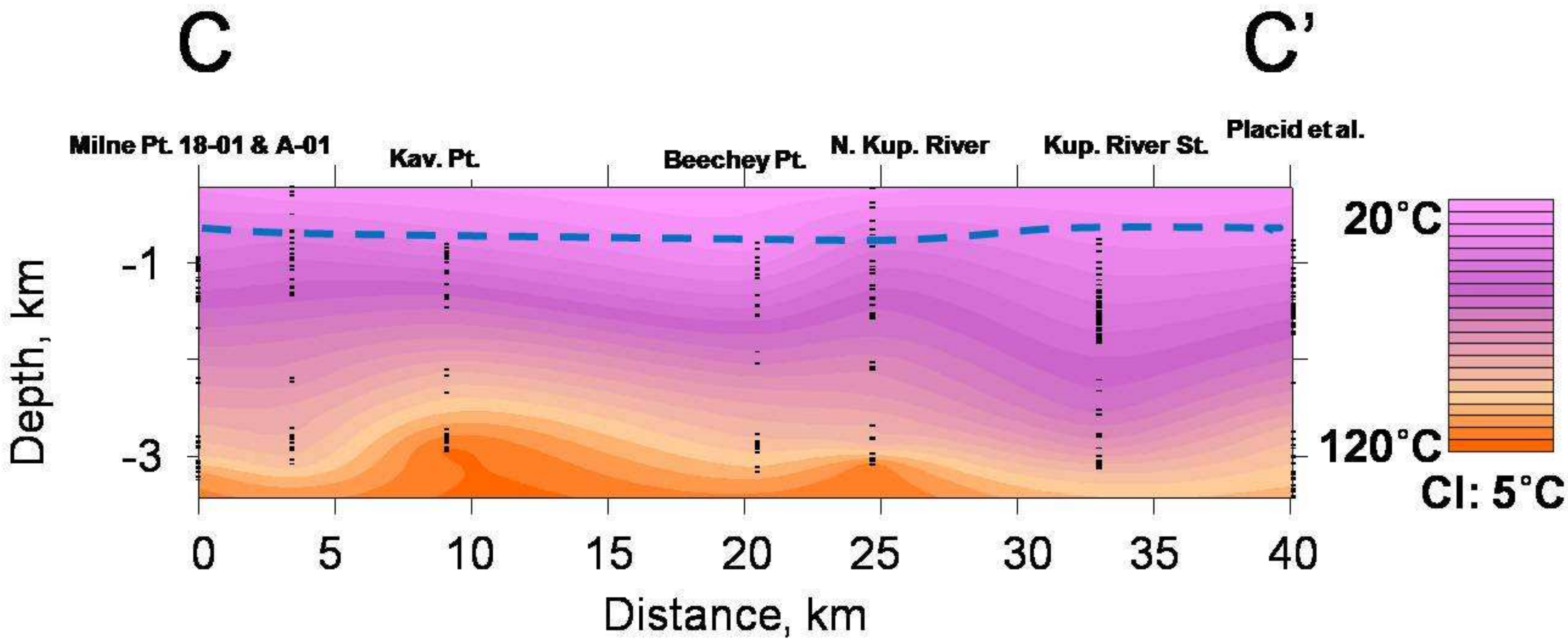


Figure 26. Spatial variations in subsurface temperature (˚C) patterns derived from BHT for the C-C' cross-section with the extent of permafrost overlain and shown by a blue dotted line.

The data set did not include enough information to map out the extent of permafrost in the A-A’ cross-section. The permafrost picks were available for all but four wells in the B-B’ and C-C’ cross-sections. When data was unavailable the permafrost depths were inferred from neighboring wells.

Chapter 6. Discussion

The lithostratigraphy of the central North Slope study area can be broadly summarized as follows. The deepest sediments encountered in the wells used in this study are sands and shales of the Mississippian through Triassic Ellesmerian megasequence. Carbonates of the Lisburne Group, which occur in the lower part of the megasequence, were encountered only in the East Harrison Bay well, in the westernmost part of the study area. The Ellesmerian sediments are overlain by the shale-dominated Beaufortian megasequence of Jurassic through Lower Cretaceous age. The shaley upper Ellesmerian sediments, the Beaufortian section, and the lower Brookian form a shale-dominated wedge which dips and thins to the east (Figs. 6, 12). However, included within this shale-dominated interval are the Ivishak sands (Ellesmerian), which are the host for the prolific Prudhoe Bay field, and the Kuparuk sands (Beaufortian), which are the reservoir rocks for the Kuparuk field. The uppermost sedimentary sequence consists of sand-dominated sediments of the Upper Cretaceous through Tertiary Brookian megasequence.

Although most of the Ellesmerian and Beaufortian sediments were deposited in marine environments and would have contained waters of normal seawater salinity at the time of their deposition, most of this section is now occupied by waters of much lower salinity. Exceptions are the hypersaline waters encountered in the E. Harrison Bay well and waters of nearly seawater salinity which occur immediately below the large shale wedge. Hanor et al. (2004) attributed the presence of hypersaline waters in the NPRA to an evaporitic source within the Lisburne carbonate sequence. The presence of fresh waters in marine sediments can be attributed to flushing by meteoric water during periods where there was subaerial exposure of part of the sequence. Non-marine sediments were deposited in the northeast part of the area during Sadlerochit time (Fig. 4), and a major depositional break and erosional surface developed at the time of the Lower Cretaceous Unconformity (LCU) (Figs. 4 and 6). Boles et al. (1996) invoked prolonged fluid flow in sediments beneath the LCU to account for the pervasive diagenetic alteration they documented in sediments of Neocomian (lowermost Cretaceous) age. Siderite cements are more abundant in facies exposed to meteoric waters and less abundant in distal marine facies, which were isolated from fresh water.

The Brookian sequence consists of marine shelf, slope, and basinal sediments in the northeast part of the North Slope, but is dominated by nonmarine sediments in the southwest. Hence, topographically-driven flow of meteoric waters could have existed here for much of the latest Cretaceous through the Cenozoic. Kharaka and others (1988) in their analysis of formation waters from the Lisburne, Sadlerochit, and Barrow units in the NPRA noted that the δD and $\delta^{18}O$ isotopic systematics supported the hypothesis that a meteoric end member was introduced into those units during times when the climate was much warmer than it is today. Waters approaching seawater salinity in Brookian sediments are found in the eastern part of the study area immediately above the large regional shale wedge (sections A-A’ and C-C’). These salinities may represent residual marine salinities in sediments deposited in the distal marine portion of the depositional system. The lowest salinities encountered in the Brookian section occur in the central portion of section A-A’, between the Colville Delta and Put wells. At this location there is a lens of water having salinities of less than 5000 mg/L that extend from near the surface to depths of over 1 km. The results of this study support Woodward’s (1987) findings that low salinity waters occurs in the Ivishak sand, which hosts the Prudhoe Bay field (Fig. 22). This is evidenced by the lens of low salinity Ivishak water (Fig. 25) which is situated within the thick regional shale-dominated interval. The Ivishak shows up as sandier (gray) beds bounded above and below by shalier beds(green) approximately midway within the thick shaley interval in several of the wells in the sand bed distribution cross-section A-A' (Fig. 12).

Unlike the study conducted by Hanor et al. (2004) in the NPRA, which provided hydraulic head data that supported the existence of a regional northward fluid flow system, the calculated hydraulic head data derived in this study are too sparse in the central North Slope area to establish much about the nature of regional topographically-driven flow that may be here occurring today. The calculated heads at a depth of 1 km range from approximately 150 m to over 280 m (Fig. 21) and are thus consistent with over pressuring due to differences in topographic elevation, but additional head data are needed to the south toward the Brooks Range to confirm this. It would also be useful to obtain daily records of drilling mud weights and direct down hole pressure measurements. The present head data support the possibility that there is an area of convergence and thus upwelling of fluid flow in the central part of the study area, approximately 15 km inland from the coastline (Fig. 21).

There are some significant spatial variations in temperature, as determined from corrected bottom hole temperatures (Figs. 24-26). In general somewhat warmer temperatures are encountered at depth in the coastal wells (sections B-B' and C-C'). These warmer temperatures support the hypothesis that the near coastal area in the study area may be a zone of fluid upwelling, which is transporting warm waters upward and toward the coast. Collett (1988) made a map (Fig. 27) of the calculated and projected geothermal gradient in the North Slope which shows an area of elevated geothermal gradient within the present study area which corresponds spatially to the possible area of fluid convergence determined from hydraulic heads (Fig. 21). Collett also shows two additional areas of elevated geothermal gradient to the west which correspond spatially to areas of upwelling documented by Hanor et al. (2004).

One of the goals of this study was to test the hypothesis that the API gravities of the central North Slope oils have been influenced by water washing and/or biodegradation by examining the relation between API gravity and formation water salinity. The dynamic introduction of low-salinity meteoric waters has the capacity for lowering API gravities through water washing or through the introduction of nutrients that support microbial bidegradation. However, there is no clear relation (Figs. 22-24). For example, the calculated salinities of formation waters in the Prudhoe Bay field, which contains light oils, and the West Sak field, which contains heavier oils are approximately the same. One possibility is that the hydrocarbons in the Prudhoe Bay field were introduced well after flushing of the reservoir by low salinity waters and that the shallower West Sak oils have been impacted by a more dynamic and recent flow regime. The very high bicarbonate concentrations in the few waters analyses, which are available for the central North Slope are consistent with degradation of organic carbon, as has been proposed for the Mackenzie Delta region (Grasby and Chen, 2007).

Also of interest in this study was the possibility that the advective transport of heat by subsurface fluid flow might play a role in controlling the depth to the base of permafrost in the central North Slope. While there are variations in subsurface temperature and temperature gradient in the study area, which may be related to advective heat transport, there does not appear to be a significant variation in the depth to the base of permafrost (Figs. 25 and 26), which suggests that surface temperature is the primary control on permafrost and/or that the thermal anomalies at depth do not propagate to the near surface.

Chapter 7. Conclusions

The results of this study demonstrate that the Permian though Cenozoic age sediments of the central North Slope foreland basin have been significantly flushed by low salinity waters. Although isotopic analyses of these waters are not available, it is likely that they have a major meteoric component, as is the case in the National Petroleum Reserve Alaska (NPRA) immediately to the west (Kharaka et al. 1988). There may have been several periods of time in which meteoric waters were introduced into the section, including the Triassic, during the development of the Lower Cretaceous Unconformity (LCU), and following the uplift of the Brooks Range. Diagenesis associated with fluid flow during the LCU may have provided pathways for later hydrocarbon migration at the Prudhoe Bay field (Boles et al., 1988). Meteoric flow has the potential for altering the API gravity of crude oil through water washing and/or biodegradation. However, there is no clear relation in the central North Slope between salinity and API gravity. It is possible that the Prudhoe Bay oils, which are light, were emplaced following invasion of fresh waters and the overlying Kuparuk oils, which are heavier, have been significantly impacted by fresh waters following their migration and entrapment.

Spatial variations in hydraulic head (Hanor et al., 2004) and numerical modeling of fluid flow (Nunn et al., 2005) support the current existence of a regional topographically-drive meteoric flow regime in the NPRA. Such a regime probably exists today on the North Slope to the east, but additional pressure, head, and temperature data are needed to verify it. There is no clear relation between depth to the base of permafrost in the study area and the elevated temperatures which may reflect fluid upwelling.

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Vita

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